Public Service Commission of Wisconsin
& The Statewide Energy Efficiency and Renewables Administration

Environmental and Economic Research and Development Program

Executive Summary

October 2008

Impacts of Past and Future Changes in Climate and Atmospheric CO_2 on Wisconsin Agriculture

Prepared by:
Christopher J. Kucharik
Center for Sustainability and the Global Environment (SAGE)
The Nelson Institute for Environmental Studies
University of Wisconsin-Madison

Shawn P. Serbin
Department of Forest and Wildlife Ecology
University of Wisconsin-Madison

This report in whole is the property of the State of Wisconsin, Public Service Commission of Wisconsin, and was funded through the FOCUS ON ENERGY program.

focus on energy[sm]
The power is within you.

Executive Summary

Background

Both farmers and agricultural policy-makers need information about how climate change will affect agriculture. For growers and agri-business to respond to market and policy incentives on energy crops, they will need to understand the long-term viability of their investments in the face of shifting climate conditions. The programs of state and federal agriculture and energy agencies will be more efficient and effective if we know what kind and how much biomass a given region can produce under average and extreme conditions in the future.

The grand challenge confronting agriculture is to better understand how these cropping systems and farmers have responded to changes in the climate system, and whether future climate change and increasing atmospheric CO_2 may make agro-ecosystems more vulnerable to failure. Climate change and increased variability pose a real threat to the stability of agro-ecosystems in the long term, jeopardizing food and economic security. While many studies have demonstrated the sensitivity of cropping systems to climate, no consensus has yet emerged regarding the specific mechanisms responsible for causing such changes, or how these play out in specific regions. This makes it virtually impossible to implement local policy to protect agricultural lands. Our studied focused on a single important question: ***How has previous climate change and variability impacted corn and soybean production across Wisconsin, and how might future atmospheric changes challenge farmers?***

Research Objectives

To address our key research question, we focus on three main objectives geared towards studying the connection of Wisconsin climate with agriculture: 1) Develop a multi-decadal, high-resolution gridded (8 km) daily record of maximum and minimum temperature and precipitation observations, and annual crop yields (corn and soybeans) across Wisconsin for the 1950 to 2006 period; 2) quantify the actual trends in climate and quantify statistical relationships between seasonal weather indices and corn and soybean yields for 1950-2006 to determine how climate change and weather variability have contributed to trends and variability in U.S. Department of Agriculture (USDA) yield data; 3) use statistical modeling in conjunction with results from (2) and Global Circulation Model (GCM) scenarios of future climate change through the year 2100 to delineate how crop yields may respond to atmospheric changes.

Methods

We used a combination of newly gridded climate data across Wisconsin, USDA county level corn and soybean yield data, and statistical modeling tools to study the relationships between monthly average maximum and minimum temperatures and precipitation during the period of 1950-2006. Statistical relationships for this period were then used in combination with GCM output of future climate across Wisconsin to better understand how global warming through the year 2100 may impact crop productivity at the district level. Here, we summarize the work performed as part of each segment of our project:

1. Development of multi-decadal, high-resolution gridded daily climate dataset for Wisconsin

A multi-decadal climatic data set was developed for 57 years (1950 – 2006) consisting of daily and monthly precipitation (P_{Total}), maximum temperature (T_{max}), and minimum temperature (T_{min}) across Wisconsin using observations from ~176 weather observation stations. The data set was constructed at 8 km (5.0’) latitude-longitude resolution using an automated Inverse Distance Weighting (IDW) interpolation scheme. We performed a rigorous test of the predictive accuracy of the IDW gridded surfaces using 104 stations withheld in the production of the climate grids in a post-gridding validation step. The mean bias errors were reasonable, ranging from -0.75 to 0.96 °C for temperature and -0.04 to 0.08 mm for precipitation, on average, across all climate divisions. Our results suggest a high degree of explained variation for daily temperature ($R^2 \geq 0.97$) and a moderate degree for daily precipitation ($R^2 = 0.66$), whereby the realism improves considerably for monthly precipitation accumulation totals (R^2=0.87). We also observed a small seasonal variation in accuracy of the climate grids, with decreasing predictive capability as precipitation totals increased during the wetter summer months, when more precipitation originates from convective forcing. The grids show clear and coherent spatial patterns in temperature and precipitation that are to be expected for this region. For example, latitudinal gradients in temperature and precipitation are observed across the state, with decreasing temperature towards the north and increasing accumulation of precipitation toward the Northwest in the summer.

2. Examining the connections between climate variables and crop yields across Wisconsin

An important area of agronomic research is the study of connections between crop productivity and climate so that new crops, hybrids, and management strategies can either combat any negative impacts of future climate change, or take full advantage of new, favorable climate regimes. In Wisconsin, because an ecological *tension zone* dissects the main corn and soybean-growing region, agro-ecosystems in northeastern counties may respond differently to climate changes comparatively to southwestern counties. Therefore, a spatially explicit study is warranted to better understand how previous climate variability has impacted crop productivity. To address this need, we studied corn and soybean yields in relation to climate using county level USDA-NASS data and our gridded 8-km daily climate dataset from 1950 to 2006. The daily climate dataset was aggregated to the county level to match USDA county yield information. Maximum (*tmax*), minimum (*tmin*), and average (*tavg*) temperature and total precipitation (*prcp*) were determined for each Wisconsin county (n=72) at daily and monthly temporal scales for the entire period.

In order to study the response of each crop to climate variability in each county, we used regression models based on monthly maximum temperature, minimum temperature, and precipitation as predictor variables. We first studied independent regression relationships between percent yield anomalies and climatic variables for each crop in every county. We chose to assess the relationships for months spanning March through October, which encompasses the general growing period length. We used a second order polynomial regression given that temperature and precipitation can have a non-monotonic effect on yields each year.

3. Quantifying the impact of recent climate change on corn and soybean yield trends

We focused on the last 31 years (1976-2006) of the data record and calculated monthly climate and corn and soybean yield trends for each county. The beginning year of 1976 was chosen to coincide with the initiation of the most recent period of sustained warming in the 20th century, which followed a period of cooler temperatures from the 1950s through the early 1970s. We calculated trends for (1) county corn and soybean yields (Mg ha^{-1} yr^{-1}) and the (2) county average monthly *tmax*, *tmin*, *and tavg* temperatures (ºC yr^{-1}) and *prcp* (mm yr^{-1}) for each month of the year using linear regression analysis and the JMP (v.5.01) statistical software package (SAS, Cary NC). We determined that 61 counties in Wisconsin had continuous corn and soybean yield records for 1976-2006, and computed a total of 2928 climate variable regressions (12 months x 4 variables x 61 counties) and 128 total crop yield regressions as a first step. We also computed multiple month average climate values for *two* and *three* consecutive month periods (e.g., Mar.-

Apr., Jun.-Aug., Aug.-Sep., etc.), allowing for additional predictor variables to be tested as part of the regression analysis.

In order to study the relationship between crop yield trends and climate trends across Wisconsin, we developed multiple regression models using the monthly, two-month, and seasonal (i.e. three-month) composite *tmax*, *tmin*, *tavg*, and *prcp* values as predictor variables and corn and soybean yield trends as the response variables. To do so, we first studied the independent regression relationships between all climate variable trends and yield trends using all 61 counties as replicates. We selected the most important predictor variables based on their coefficient of determination (R^2) values. In general, all predictor variables that were ranked high (based on R^2 values) had a significant relationship with corn and soybean yield trends ($P < 0.001$).

4. Assessing potential impacts of future climate change and increased atmospheric CO_2 on Wisconsin corn and soybean yields

We used a meta-analysis and results from recent field experiments in Illinois and other locations in the U.S. Midwest to investigate how increasing atmospheric CO_2 may impact corn and soybean yields in Wisconsin. We then coupled output from two Global Circulation Models (GCMs) with our statistical analyses of how corn and soybean yields have been previously affected by climate variability across Wisconsin to numerically model how future changes in climate may impact agricultural productivity through the year 2100. The approach calculates what the percent yield deviation would be compared to 10-year average yields during the 1997-2006 time period. Results were developed for each of Wisconsin's nine climate districts to better understand whether some regions will be more or less impacted by future changes in climate.

Key Results

Climate dataset accuracy

We performed a rigorous test of the predictive accuracy of the inverse distance weighting gridded climate data surfaces using 104 stations withheld in the production of the climate grids in a post-gridding validation step. The mean bias errors appear reasonable, ranging from -0.75 to 0.96 °C for temperature and -0.04 to 0.08 mm for precipitation, on average, across all climate divisions. Our results suggest a high degree of explained variation for daily temperature ($R^2 \geq 0.97$) and a moderate degree for daily precipitation ($R^2 = 0.66$), whereby the realism improves considerably for monthly precipitation accumulation totals (R^2=0.87). We also observed a small seasonal variation in accuracy of the climate grids, with decreasing predictive capability as precipitation totals increased during the wetter summer months, when more precipitation originates from convective forcing. The grids show clear and coherent spatial patterns in temperature and precipitation that are to be expected for this region. For example, latitudinal gradients in temperature and precipitation are observed across the state, with decreasing temperature towards the north and increasing accumulation of precipitation toward the Northwest in the summer.

Wisconsin Climate trends

As part of our work, we calculated trends in climate variables across the state of Wisconsin from 1950-2006 to quantify recent climate change. In summary, annual average nighttime low temperatures have increased by 0.6 to 2.2ºC, whereas the annual average daytime high temperatures have warmed by 0.3 to 0.6ºC. Annual average precipitation has increased by 50-100 mm in the central and southern portions of the state, while precipitation across the far northern portion of the state appears to have declined by 20-60 mm since 1950, with the most pronounced decrease occurring during summer. On a seasonal basis, warming temperatures are more pronounced during winter and springtime, and nighttime temperatures are warming faster than daytime high temperatures. Some cooling trends in daytime high temperatures were observed during late summer and fall, particularly in the northeast and far southwest portions of the state. We calculated that the length of the growing season has increased by 5 to 20 days, with the greatest change in the central and northern part of Wisconsin. The annual number of days each year with low temperatures less than 0ºF has diminished substantially, while the number of days each year with highs greater than 90ºF has remained relatively constant, which is in contrast to what has been projected by climate models.

Climate effects on Wisconsin corn and soybean yields

Across southwestern regions, corn yield variability was most influenced (ranked by R^2 values) by July maximum temperatures and July precipitation whereas across the northeast, daily high temperatures in September impacted corn yield variability the most. In contrast, soybeans were most affected by precipitation in July and August over the west central and southeast, and by minimum daytime temperatures during May for northeastern counties close to Lake Michigan. Small increases in average high temperatures during July and August (e.g., 2 – 4ºC), which are on the same order of magnitude that is projected under future warming scenarios with climate models, were correlated with annual yields that were 10 to 30% lower than the expected, average values. Surprisingly, positive summertime precipitation anomalies of +50-100% translated into yield increases of only 3% to 11%. Overall, crop yields were favored by cooler than average daytime high temperatures in late summer, and above normal temperatures in September.

The IPCC (2007) reported that a mean local temperature increase of 1-2ºC in the mid- to high-latitudes where agricultural adaptation took place could boost corn yields by 10-15% above the baseline. A 2-3ºC increase in mid- to high-latitudes coupled with adaptation could still allow crop yields to increase above baseline values, but a 3-5ºC increase would mean yields would fall to the approximate baseline value, and would decrease by 5-20% without some type of adaptive strategy. Our composite results support these generalizations, as an increase of 2ºC in the maximum monthly average temperatures in July and August translated into yield losses of 6% for corn and 2-4% for soybean. A warming magnitude of 4ºC in monthly average maximum temperatures in July and August across Wisconsin could lead to corn and soybean yield losses of 22-28% and 13-24%, respectively, if adaptive measures do not occur.

Impacts of recent climate change on Wisconsin corn and soybean yield trends

Corn and soybean yield trends across Wisconsin have been favored by cooling and increased precipitation during the summer growing season. Trends in precipitation and temperature during the growing season from 1976-2006 explained 40% and 35% of county corn and soybean yield trends, respectively. Using county level yield information combined with climate data, we determined that both corn and soybean yield trends were supported by cooler and wetter conditions during the summer, whereby increases in precipitation have counteracted negative impacts of recent warming on crop yield trends. Our results suggest that for each additional degree (ºC) of future warming, corn and soybean yields could potentially decrease by 13% and 16%, respectively, whereas modest increases in precipitation (i.e. 50 mm) during the summer could help boost yields by between 5-10%, counteracting the negative effects of increased temperature. While northern U.S. Corn Belt regions such as Wisconsin may benefit from climate and management changes that lengthen the crop-growing period in spring and autumn, they are not immune to decreased productivity due to warming during meteorological summer.

Potential impacts of future climate changes and increased atmospheric CO_2 on Wisconsin corn and soybean yields

New experimental data suggests that C_4 photosynthesis (corn) is already saturated at the current levels of atmospheric CO_2, and thereby any more increases in CO_2 will not be effective at boosting productivity in the future. In one key study by Leakey et al. (2006) performed in Illinois, they found that elevated CO_2 (550 ppm) did not stimulate an increase in photosynthesis or yield compared to current levels. In the case of soybeans, it appears that increases in yield could still occur as CO_2 increases in the atmosphere, but the projected increase is approximately 50% less than the original studies that were performed using enclosures or chambers. It is suggested that across Wisconsin, soybean yields may be increased by approximately 13-15% as CO_2 levels climb towards 550 ppm by 2050.

The first result that we saw when looking at crop yield responses in the future is that there are very large discrepancies in the future projections between the two sets of climate model runs, signaling that there are significant differences in the climate output between the two scenarios we used. In general, the largest changes in corn yields are expected to occur in the southern part of the state (climate districts 7-9), and towards the latter half of the 21^{st} century. Those deviations, when normalized according to current average yields, suggest that 30-60% corn yield losses (e.g., ~40-80 bu ac^{-1}) are possible in the latter half of the 21^{st} century attributed to climate change. Across the northern districts, a warmer climate during the growing season may actually favor increases in corn yields by up to 10% according to the CCC climate model (e.g., climate district 2), but those results were generally not replicated when using HAD climate model output to drive the simulations.

In general, the largest changes in soybean yields are expected to occur in the southern part of the state in climate districts 7 and 8, after about 2060. Those deviations, when normalized according to current average yields, suggest that 30-60% soybean yield losses (e.g., ~15-30 bu ac^{-1}) are possible in the latter half of the 21^{st} century attributed to climate changes. Across the northern and central districts – along with climate district 9 – the impacts of climate change on soybean yields are mixed. For example, the results using the CCC climate model output suggest that soybean yields will remain around +/- 10% of the current yield values through the end of the century, while the HAD model climate output causes soybean yields to decrease by 30-60% during the middle part of the 21^{st} century, only to rebound in the late stages of this century.