Analyzing the Impact of Climate Change on Future Wheat Yields

Eric Manges

*Department of Geological and Atmospheric Sciences, Iowa State University, Ames, Iowa*

Dr. Mike T.C. Chen– Mentor

Professor

Dr. Justin Glisan– Co-Mentor

Research Scientist

**ABSTRACT**

This thesis analyzes the effects of increased carbon dioxide concentrations in the earth’s atmosphere along with corresponding temperature increases associated with it based on RCP data outputs. Through the manipulation of precipitation variables in the APSIM Model the probability of wheat yields matching the Iowa average yield determined by the USDA is then analyzed. Precipitation variables that are changed include annual rainfall amounts and total available ground moisture of ground layer from 260cm deep. Results show that future carbon dioxide concentrations and temperature changes will result in dramatic probability decreases in reaching Iowa average yield by the year 2100. The most dramatic effect was the reduction of ground water on the total yields and a drop of annual precipitation from 10 to 25 percent had minimal to marginal impact of the yield probabilities. Future implications of the research depicts a grim outlook on future crop yields for wheat in Iowa. Yields most likely will be unable to adjust to increased demand and the global impact will be catastrophic if wheat genetics and growing habits are not altered.

---

1. **Intro**

Human impact on the surrounding environment from a large-scale perspective is clear. Decreasing ice sheets in the poles and the thawing tundra’s may be the most visible impacts of climate change but yet their human impacts thus far are small. Most population centers are at the mid-latitudes and are thousands of miles from the direct impacts of melting ice. Projected sea level changes and ocean current will have a dramatic effect on the global economy in the future but still the small scale and current perspective is missed.

Rising oceans and temperatures still have yet to dramatically impact human’s wallets and most importantly our stomachs. Global warming’s impact on crops is still the defining questing when predicting the severity of the impact of global climate change. Still many uncertainties surround how precipitation around the world will be affected by temperature increases (Huntingford, 2005). It’s been documented in
corn that precipitation variations from average annual totals have little impact on overall corn yields but rather the timing of that rain had the biggest effect. Mid-summer temperatures in July in the USA typically cause the most water stress on the plant with temperatures exceeding 90°F in the corn belt. The higher levels of rain in mid-summer in most cases had the most impact in increasing yields (Changnon, 2003). By mid-summer most crops have already flowered and have begun the processes of seeding, making this a key time for moisture absorption.

By using a rule of thumb that crop growth becomes more difficult after 90°F most locations in the mid-latitudes are much more rarely exposed to such temperatures. But closer to the equator this temperature is more easily reached. Where the globe can see the biggest crop impact in the coming years is food production closer to the equator where already plants are more stressed to produce consistent yields. With average temperatures already closer to 90°F in equatorial regions, global warming’s first impacts could potentially be seen in these areas. Driving a growing demand for crop exports in mid-latitudes and require higher yields in places such as the US and Europe. This is why it’s crucial to figure out how climate change will impact more temperate regions based on the predictions of how crop demand will only increase in the future (Godfray, 2010).

But perhaps the most dramatic effect that climate change may bring is the amplification of droughts. Droughts on their own are some of the most devastating phenomena on the planet. Entire ecosystems can be whipped out or severely crippled from a lack of water (Planton, 2013). Usually in periods of droughts plants are able to restrict their water usage and transpiration by closing stomata and stopping growth all together but over long periods of time this can result in a slower developing plant or even death (Eilmann, 2011). This makes it a key research point to keep in mind the potential impact that both lower rainfall totals and increased drought conditions may have on total yields of crops. Being able to change these parameters into crop models is crucial to accurately forecasting the impacts climate change can have but not all models behave the same.

Most agriculture models are sensitive to emissions of CO2 and their immediate effects on the net absorption of solar radiation which is why accurate models for global emissions are so crucial (Cai, 2009). To accurately forecast future crop yields makes manipulation of CO2, temperature, annual precip, and ground water levels crucial to depicting how climate change will impact crops.

2. Methods

A. Experimental Set Up

The data gathered is centered in Ames, Iowa. A location that’s mostly rural and the human impact on climate is presumably small. The crop being focused on is wheat. Corn has been researched heavily in the past and in comparison the global demand for wheat is much higher which made it the choice for the research.

The data gather begins in the year 1979 and runs to the year 2013 which includes
temperature, daily rainfall, ground water content, and yield. This data is then used to project 2100 yields of wheat based on the manipulation of the key variables of CO2 ppm, annual precipitation, ground water contents and temperature. CO2 and temperature variations were chosen based on climate change model outputs from the Representative Concentration Pathways (RCPs) database. Each RCP scenario represents different levels of CO2 and the resulting temperature change caused by it to the year 2100.

B. Representative Concentration Pathways RCP Data

With the use of global climate models that puts the regions of the globe in thousands of grids which each calculate their own energy absorption like in figure 1. Also the use of thermodynamic laws to predict the transfer of that energy between grid points if done accurately depicts the cycle of energy throughout the globe. This data can be used to estimate variables such as winds, temperature, and moisture. Then each model is used on historical information and then matched to historical observational. The comparison of the model run to the actual observation and its accuracy is then used to project into the future what the temperature effects will be with different net amounts of energy being retained or radiative forcing by the earth in watts per meter squared. To prevent guessing the impacts of increased carbon dioxide levels on the temperature the use of global climate models with temperature totals in required. Representative Concentration Pathways or RCP are global climate change models that have been run at different CO2 concentrations. Each RCP run represents different scenarios and what the global temperature impact will be by the year 2100. In this experiment, the model runs of RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5. Each number represents an increase Watts per Meter^2 or the overall energy retention increase due to the greenhouse effect. These RCP run outputs will be used as the temperature and carbon dioxide

![Figure 1. NOAA climate change model outputs from the RCP database based on different scenarios of CO2 emissions in the atmosphere and the overall temperature increase that different regions would experience by the year 2100. Part A, RCP 2.6 W/m2 amount of radiative forcing by 2100 and represents scenario where all environmental regulations are put in place and goals are met at a global scale of CO2 emission reduction. Part B, RCP 4.5 W/m2 amount of radiative forcing by 2100. Part C, RCP 6.0 W/m2 amount of radiative forcing by 2100. Part D, RCP 8.5 W/m2 amount of radiative forcing by 2100 if humans the current emissions path with no further changes at the global scale.](image)
concentration values tested in the APSIM Model.

*C. Agricultural Production Systems IMulator (APSIM) 7.8*

This model was first produced in Toowoomba, Queensland, Australia. It’s a publicly available model used to predict different plant, animal, soil, and climate conditions and their outputs.

Continuously updated by a community framework its main purpose is to aid in research and development. Crop growth is measured on a daily time step that is in square meters rather than following the growth of individual plants. The growth is governed in the model mostly by radiation, temperature, soil water, soil nitrogen, and management practices and many variables are easily manipulated to effect the yield of the plant.

Each plant’s growth follows a set of equations based on the stage or phases it’s in. 7-11 phases exist depending on the plant type which grows at different rates depending on the daily conditions of radiation, temperature, etc. (APSIM Initiative, 2016).

By using previously gathered data the model can output yields of particular plants based on the past and in this case wheat after the manipulation of variables. From earlier the variables changed were, CO2 content in the atmosphere in parts per million (ppm), temperature, annual precip, and ground water saturation. By using the RCP data (figure 1), CO2 ppm and temperature variations as variable values the 2100 yields can be determined in one graph. Then each model run can be manipulated individually for annual rainfall and ground water content. Water content is measured by total saturation of a column of soil 260cm deep.

*D. Procedure and Analysis*

Putting the RCP data into the APSIM model for CO2 ppm, and temperature change in °C for the year 2100 would give what can be expected as the yield of wheat under those atmospheric conditions. Graphing all four conditions of RCP 2.6, 4.5, 6.0, 8.5 and pre-industrial (PI) CO2 values, and current CO2 levels then reflect how crops will change and how much humans influence will be by the year 2100. Graphing the outputted yield compared to the probability of exceeding average yield levels from historical data can show what future farmers can expect under each RCP condition. This serves as the baseline without the change in annual precipitation or ground water saturation.

Throughout the model runs the pre-industrial annual precipitation and ground water content will be unchanged to also serve as a constant comparison when looking at all the other model runs. Mostly done so the viewer can understand and visibly see the small variations the figures will have for each scenario.

Once a base impact is created reflecting similar rain patterns now the manipulation of water variables can be done. This would represent the possible affect of climate change on the overall annual rain totals, and ground water saturation. By doing runs of 10% and 25% annual precipitation reduction at all the RCP levels including, PI, and Current conditions yield impacts can show the results of water stress. Also by reducing the overall ground saturation of the 260cm column of ground soil in separate simulations from 100% to 50%, and then 25% it will depict how drought conditions
over an extended period will effect crop yields.

The resulting output can then be analyzed to see what factors impact wheat yields the most. Model output will display the probability of each model run of reaching a particular yield and overall the probability of each run of hitting the Iowa average wheat yield. In doing so it can be seen how global warming will affect the production of wheat and how well areas such as Ames Iowa can absorb the increasing demand of crops in the future.

3. Results and Analysis

A. APSIM Model Output with No Precipitation Change or Ground Saturation, Just CO2 and Temperature Increase to Serve as Baseline

This run serves as the baseline to having no annual rainfall change or groundwater saturation change. From figure 2 it can be seen that although current yields are greater than pre-industrial revolution yields, as CO2 parts per million increase the probably of meeting or exceeding the Iowa mean wheat yield per hectare decreases.

All levels of CO2 after the eighty percent probability have a steep drop off of total yields. And after fifteen percent the overall yield totals increase.

The most dramatic decrease in yield came in the 936ppm scenario represented in turquoise with a fifty percent probability of only reaching 1/3 of the Iowa wheat yield average.

Both the 550 and 670 scenarios have little variation and follow a very similar pattern in their decreases in probabilities to yield totals.

Noticeably after 2500 kg/ha, the pre-industrial revolution line in blue has the steepest drop off of all the model runs and even has the least possible total yield. Current conditions of 397ppm performed overall the best with overall wheat yield.

Most disturbingly the larger the RCP used the smaller the probability was of reaching the Iowa average yield for wheat (Table 1). Current conditions performing the best is most likely due to current plants having the genetic capacity that handles current climates very well. This brings up the question of how necessary genetic modification is with such a decay in yield probabilities with the increase in temperature by the year 2100.

<table>
<thead>
<tr>
<th>CO2 Level</th>
<th>No Drought Conditions</th>
<th>-10% Annual Rain 100% Ground Water</th>
<th>-25% Annual Rain 100% Ground Water</th>
<th>-10% Annual Rain 50% Ground Water</th>
<th>-25% Annual Rain 50% Ground Water</th>
<th>-10% Annual Rain 25% Ground Water</th>
<th>-25% Annual Rain 25% Ground Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre IR</td>
<td>27.5%</td>
<td>27.5%</td>
<td>27.5%</td>
<td>27.5%</td>
<td>27.5%</td>
<td>27.5%</td>
<td>27.5%</td>
</tr>
<tr>
<td>Current</td>
<td>91.5%</td>
<td>92%</td>
<td>89%</td>
<td>86%</td>
<td>87.5%</td>
<td>77%</td>
<td>72%</td>
</tr>
<tr>
<td>RCP 2.6</td>
<td>72%</td>
<td>70%</td>
<td>71%</td>
<td>64%</td>
<td>53%</td>
<td>52.5%</td>
<td>41%</td>
</tr>
<tr>
<td>RCP 4.5</td>
<td>58%</td>
<td>57.5%</td>
<td>52.5%</td>
<td>51%</td>
<td>42.5%</td>
<td>45%</td>
<td>37.5%</td>
</tr>
<tr>
<td>RCP 6.0</td>
<td>45%</td>
<td>45%</td>
<td>44%</td>
<td>39%</td>
<td>36%</td>
<td>35%</td>
<td>27%</td>
</tr>
<tr>
<td>RCP 8.5</td>
<td>15%</td>
<td>14%</td>
<td>11%</td>
<td>8%</td>
<td>8.5%</td>
<td>10%</td>
<td>9%</td>
</tr>
</tbody>
</table>

Table 1. The probabilities of each individual model run of reaching the Iowa average wheat yield with an error of +/- 1%.
Figure 2. Graph represents the probability of wheat yields exceeding or meeting the average yield in Ames Iowa based on 1979-2013 Metadata through the Apsim Model. Each line on the graph represents different levels of CO2 in parts per million and resulting temperature shift according to NOAA’s Climate Model Representative Concentration Pathways and how it effects the probability of the yield exceeding 100%. Black line serves as the Iowa average yield of wheat in Kilograms per Hectare. Blue data is CO2 levels before industrial revolution, Red is current CO2, Green is case of 2-degree Celsius temperature increase, Orange is case of 3-degree Celsius temperature increase, Pink is 3.5-degree Celsius temperature increase, and turquoise represents 5.5-degree Celsius temperature increase “business as usual scenario”.

B. APSIM Model Output with 10% and 25% Annual Precipitation Change No Ground Saturation Change and same CO2 and Temperature Increase as Baseline

From figure 3 now that annual precipitation totals are decreased the overall yields are noticeably decreasing as well. Also, the probability of meeting or exceeding the mean wheat yield is decreasing. Still not by a very significant amount mostly due to no huge change in ground water content which reflects typical environments hardy ability to maintain ground moisture even during periods of drought.

Leaving the pre-industrial revolution unchanged is used to help with other CO2 model run comparisons. Once again the 550 and 670 model runs exhibit very similar
behaviors with the 550ppm performing slightly better.

All model runs show a steeper decrease in yields than the base condition. Annual precipitation amounts do have an impact on the overall probabilities of exceeding yield totals. The impacts range from 6-2% at most from the base condition and overall have little small scale impact but if that impact was felt over a large region the yield impact would be massive.

C. APSIM Model Output with 10% and 25% Annual Precipitation Change and 50% Ground Saturation Change and same CO2 and Temperature Increase as Baseline

With only half the ideal amount of ground water present and the addition of lost rainfall, yields continue to drop as seen in figure 4. As well as the probability of meeting or exceeding the mean wheat yield in Iowa (Table 1). This is where large variations are visible from the initial condition. RCP conditions 2.6 and above see probabilities of yield meeting the Iowa average decrease by 8-20%.

The large impact from a reduction in groundwater is first visible in these model runs. It highlights the importance of ground moisture for plant growth and the susceptibility of wheat to drought conditions if sustained over a long period.

D. APSIM Model Output with 10% and 25% Annual Precipitation Change and 25% Ground Saturation and same CO2 and Temperature Increase as Baseline

Only a quarter of the groundwater and the reduction in annual precip has the largest impact on the overall yield. In all cases besides RCP 8.5 performing the worst overall and resulting in massive loss of yield which can be seen in figure 5.

Current conditions through RCP 6.0 have decreased in probabilities of hitting the Iowa average yield of 10-30%. RCP 8.5 flat lines with the lowest probability of 9%.

Although possible for wheat to reach normal yields this extreme scenario points out the dramatic effect a sustained drought can have on a crop. This kind of situation spread out over the entire grain belt of the US would be catastrophic for the annual food production of the US. According to the USDA, the 2017 forecasted value of exported crops will be 134.0 billion dollars. If these conditions were to occur by the year 2100 no matter what CO2 level, the yield, and economic impact would be massive. The usual excess of crop production in the US could by this point diminish so much that the necessity of importing basic crop would be required.
Figure 3. Graphs represent the same data and information as figure 1 just with a reduction in the annual precipitation in both model runs. With completely saturated soil to a depth of 260cm from top to bottom, the reduction of annual was 10% and 25%.

Figure 4. Graphs represent the same data and information as figure 1 just with a reduction in the annual precipitation and ground water content of soil 260cm deep that’s only 50% saturated. From top to bottom, model output represents 10% and 25% reduction in annual rainfall.

Figure 5. Graphs represent the same data and information as figure 1 just with a reduction in the annual precipitation and ground water content of soil 260cm deep that’s only 25% saturated. From left to right model output represents 10% and 25% reduction of annual rainfall.
E. Total Model Analysis

Each increased carbon dioxide scenario performed worse overall after each model run as seen in figure 6. The reduction of annual rainfall of 10% to 25% had little difference in most outputs. Ground water reduction had an amplification effect on the probability of yields in each scenario except RCP 8.5.

With RCP 8.5, the probability of reaching the Iowa average was the least. Each reduction of rainfall had little impact and each reduction of ground water had little impact. This is most likely due to wheat’s current genetic makeup being unable to cope with those temperature variations forecasted in RCP 8.5.

In RCP 6.0, across all scenarios, there isn’t a 50% of reaching the Iowa yield average. Ground water and annual rainfall reduction did have an impact on yield but still at this point the current genetics of wheat cannot perform at a level necessary to have consistent production and overall would dramatically impact the US food production.

The RCP 4.5 run overall had nearly a 20% reduction of probability once all the annual rainfall totals and groundwater reductions were implemented. This shows that current wheat genetics could withstand optimum moisture conditions but overall the yields would be largely affected by temperature increases.

Also, the RCP 2.6 still had respectable probabilities when moisture conditions were optimum. But after the reduction in annual rainfall and groundwater, it saw a worst-case reduction of 35% probability of reaching average Iowa yields by the year 2100. This case had the 2-degree Celsius increase and represented the most optimistic outlook for the global increase in temperature by the year 2100. At this point, wheat yields would still be reasonably high enough for Ames, Iowa to produce to a level within usual demand.

The current carbon dioxide level condition performed by far the best out of all the scenarios. It even handled reasonably well the drought condition. Even with the worst drought conditions it still performed better than all RCP runs.

Compared with all the scenarios the pre-industrial revolution carbon dioxide level showed the second worst yield probabilities. This most likely is due to current wheat genetics adapted to current CO2 levels. For this reason, it should be considered an outlier from the data.
4. Discussion

RCP scenarios represent global averages, not local US average. Use of climate change model output for the US specifically would give a more accurate output of actual yield impact by the year 2100.

On a global scale wheat is the most popularly grown crop according to the Food and Agriculture Organization of the United Nations. Wheat is annually grown on 211 million hectares across the globe as of 2002. It’s abundant use on a global scale is why it was chosen for this experiment as well in part with the APSIM climate change model background acknowledging indicating wheat performed the best compared to other crops when tested in real life experiments. Noticeably in Ames wheat isn’t the most grown crop, but rather corn and also across the US according to the USDA-ERS. By using climate data from Ames it should be taking into account that yield averages would have a smaller sample size and thus the precision of the results could have a substantial error.

As mentioned in the results and analysis section d, RCP 2.6 had the most forgiving outlook by the year 2100. Its temperature increase was 2°C and actual fits very similarly the impact that urban heat islands have on the surrounding environments. A comparison of urban heat island can help like mentioned in the intro to bring global warming down to a more local level.

Figure 6. Graph of all temperature and CO2 variations and their probability of reaching the Iowa average yield per hectare. Each drought scenario represents a graph from the figures previously given.
Urban heat islands are areas of human modification to the surface at a large enough scale to impact the surrounding weather. Areas all across the world in North America, East Asia, and Europe that exhibit vast variations in temperature and precipitation from their surrounding environments can be categorized as a heat island (Oke, 2006). Urban locations largest impact is the balance of heat absorption and emission and can be calculated using the surface energy balance equation.

\begin{equation}
\alpha Q + \alpha_a L + Q_t = \varepsilon \sigma T_o^4 + \tau c(T_o - T_s) + k \frac{dT}{dz} l_{z=0} + \lambda E
\end{equation}

Which can be further simplified down to

\begin{equation}
(1-a)I + L^* + Q_t = H + \lambda E + G
\end{equation}

By breaking down this equation into components the urban impact on the earth’s surface can be understood. Surface reflectivity of the sun’s radiation or albedo \([a]\) for most building materials is much higher than that of vegetation or bare ground and causes less radiation to be reflected back into space, meaning more energy goes into heating the surrounding air. Human sourced heating from buildings, cars, etc or anthropogenic heating \([Q_r]\), increases with the density of the urban population and also heats the surrounding environment and increases the left side of equation (2). The energy gained is then reflected on the right side of the equation. Energy absorbed by water or Latent Heat, \([\lambda E]\), is decreased in urban environments due to more runoff caused by concrete surfaces and less vegetation causes less and less water to be available to evaporation. This results in a spike in the sensible heat flux \([H]\) (Taha, 1997).

This imbalance of heat absorption and release results in abnormal heating in cities that can be between 2°- 8°C in some examples (Taha 1997). Increases in mesoscale temperatures have been shown to effect precipitation along with it, in some cases increasing the convection in clouds and increasing precipitation totals. Also having a negative effect on abnormal heating can create urban barriers of heat that can split developing thunderstorms (Bornstein, 2000). In areas of urban heat islands, the impact of rising temperatures are local and serve as a lens into the future global warming impact on the larger scale. Plant and animal behaviors in urban locations could be valuable examples to how the rest of the world will react to 2°-8°C temperature increases. By having crops tested in urban environments it’s possible to test accurately how adjusted plant genetics on a larger scale will affect yields by the year 2100.

Another important assumption used was the RCP data. Each RCP data run was created with predictions in future CO2 emissions based on current regulations and standards. Some of which were very forgiving and in the RCP 8.5 case not forgiving at all. But every day that goes by without regulatory changes to emissions the less and less likely the smaller RCP scenarios will occur. Political pressure from economic growth in the energy sector and polarizing views most political parties have for one another results in a constant juggle of regulations on emissions. Meaning that there’s no guarantee that regulations on emissions will last for the
2100 period on a global scale. It’s possible all scenarios undercut what will actually happen by the year 2100.

5. Conclusion

Initial research predictions of ground water content having the highest effect on crop growth proved true overall. But wrongfully predicted was the immediate decrease in yield probabilities once carbon dioxide concentration in parts per million increased. Overall each increase in carbon dioxide concentration and temperature decreased the probability of reaching the Iowa average yield for wheat. This alludes to the grim outlook that food production in the future will be increasingly hard to meet larger demand. All scenarios making it more difficult to trust the crop’s potential yield. With the assumption that increased temperatures will effect climate patterns and as a result annual precipitation it is further shown that wheat yields will be dramatically affected. By the year 2100 if dramatic changes to the global CO2 emissions rate don’t change the probability of Ames, Iowa meeting the average yield of Iowa will decrease significantly.

6. Acknowledgements

Thank you Dr. Mike Chen for your guidance and help throughout the semester and thank you Justin Glisan for your above and beyond help with this thesis.


