Climate Change: What to expect and how will it affect feedstock production options?

Jerry L. Hatfield (Plant Physiologist and Laboratory Director), National Laboratory for Agriculture and the Environment, USDA-ARS, 2110 University Blvd, Ames, IA 50011

jerry.hatfield@ars.usda.gov

Jeremy W. Singer (Agronomist), National Laboratory for Agriculture and the Environment, USDA-ARS, 2110 University Blvd, Ames, IA 50011

Abstract

Climate change has been occurring and the expectation is that the rate of change will increase over the next 50 years. Increases in temperature, especially, minimum temperatures, along with a projected increase in extreme temperature events will increase the rate of vegetative plant growth and decrease the length of the reproductive period. There will be shifts in precipitation patterns during the season with a projection that the summer period will become drier over most of the United States leading to the potential for more drought occurrences in agricultural regions. Variations in temperature and precipitation are the major factors causing variation in yields among years. Examination of past maize production in Iowa and Georgia show there has been a steady increase in production; however, in the period from 1970 to 1995 in Iowa, along with the remainder of the Corn Belt, there were variations in stover and grain production by as much as 30% from the trend line. Variations due to weather were more scattered in the Georgia data. The implications, based on the increased variation in temperature and precipitation, are for more variation in agricultural production leading to more uncertainty in the reliability of biofuel supplies. Agricultural management systems will have to be developed to decrease the risk of agricultural production to climate variation in order to maintain a reliable food, feed, and fuel supply.

Introduction

Climate change over the next 30 to 50 years will place new stresses on agricultural production because of the increasing temperatures, increased variability in precipitation, enhanced potential for more extreme storms, and more differences within the growing season. There have been several assessments of the potential scenarios for climate change and Meehl et al. (2007) summarized that on a global basis "it is very likely that heat waves will be more intense, more frequent and longer lasting in a future warmer climate. Cold episodes are projected to decrease significantly in a future warmer climate. Almost everywhere, daily minimum temperatures are projected to increase faster than daily maximum temperatures, leading to a decrease in diurnal temperature range. Decreases in frost days are projected to occur almost everywhere in the

middle and high latitudes, with a comparable increase in growing season length." In terms of precipitation, they stated that "For a future warmer climate, the current generation of models indicates that precipitation generally increases in the areas of regional tropical precipitation maxima (such as the monsoon regimes) and over the tropical Pacific in particular, with general decreases in the subtropics, and increases at high latitudes as a consequence of a general intensification of the global hydrological cycle. Globally averaged mean water vapour, evaporation and precipitation are projected to increase" (Meehl et al., 2007). These summaries point out the expected global change in temperature and precipitation. Across North America there are expected changes in climate mirroring the worldwide changes. These have been summarized recently by Karl et al. (2009) where temperature and precipitation patterns across the United States for the next 50 years show a warming trend for most of the United States of 1.5 to 2.0°C and a slight increase in precipitation over most of the United States. Their projections of an increase in the number of days which the temperature will be higher than the climatic normals by 5°C (heat-waves) will impact agricultural systems. They also project an increase in warm nights, defined as occurring when the minimum temperature is above the 90th percentile of the climatological distribution for the day (Tebaldi et al., 2006; Karl et al., 2009). Coupled with these changes is the decrease in the number of frost days by 10% in the eastern half of the US and an increase in the length of the growing season by over 10 days. Karl et al. (2009) showed that precipitation events would change in frequency and intensity with a projected increase in spring precipitation, particularly in the Northeast and Midwest of the United States, and a decline in the Southwestern US. The increase in extreme temperature events, warm nights, and more variable precipitation will impact agriculture and agricultural production. A trend for warmer winters will affect perennial crops and weeds, and also expand the potential habitable range of

some insect and disease pests. Although there is uncertainty about the absolute magnitude of the changes over the next 50 years, there is general agreement that CO_2 levels will increase to near 450 µmol mol^{-1} (ppm), temperatures will increase by 0.8 to 1.0°C, and precipitation will become more variable as defined in the IPCC AR4 analysis (IPCC, 2007). Changes in temperature have caused longer growing seasons and directly impacted phenological phases (Schwartz et al., 2006; Wolfe et al., 2005, Xiao et al., 2008; Karl et al., 2009). There are changes occurring in climate and these will directly and indirectly affect plant growth and ultimately biofuel production. In this paper we summarize some of the potential scenarios in climate change and relate these to plant production in order to demonstrate the impact of climate change on biofuel production.

Climate Change Scenarios

Across the United States there will not be one singular climate trend over the next 40-50 years. There will be regional differences induced by the combinations of landforms and circulation patterns. Temperatures across North America are expected to increase; however, the largest increases are expected in the northern latitudes above 50°N with more moderate increases in the remainder of North America (Christensen et al., 2007). The projected rise in mean temperature for the mid-continent regions by 2050 is 2.0°C with an uncertainty range of ±1.0°C. In the northern latitudes there would be more warming during the winter months, while throughout the mid-continent regions less seasonal variation will be evident (Christensen et al., 2007). Across the mid-latitudes, there will be a greater increase in the nighttime minimum temperatures than the daytime maximum temperatures. One aspect important to agriculture is the projected increase in the number of days with high temperatures, defined as those days that are significantly above the average temperature, because of the impact on plant stress from the rapid

change in evaporative demand on the plant. This latter aspect has implications for plant growth and development. Meehl et al. (2004) showed a decrease in the number of frost days in the year, with the largest decrease in the spring compared to the fall. There would be regional differences in these patterns because of the impact of local factors, e.g., regional atmospheric circulation patterns and pressure systems (Meehl et al., 2004). There is an increase in the number of days within the year that will exceed 32.0°C based on the use of model simulations using lower emission scenarios and if CO_2 rises more rapidly, then projected temperature increases may also be higher.

Precipitation patterns across North America have shown regional variability over the past 50 years as shown in Figure 1. The Pacific and intermountain Northwest and Southeast US have experienced declines in annual precipitation, while throughout the remainder of the US there has been increased variation even within individual states (e.g. Iowa). A critical part of the climate puzzle is the seasonal variation in precipitation and there have been shifts in the seasonal patterns with the expectation of further increases in seasonal variation. Projections for precipitation across North America for the period from 2080 to 2099 show a large continuance in the variation in the seasonal patterns of precipitation (Karl et al., 2009). Throughout the US and into Southern Canada there is an expected decrease in summer precipitation, while winter and spring precipitation for the upper portion of the US and Canada show an increase (Fig. 2). In the southern portion of the US into Mexico a large decrease in winter and fall precipitation is expected to occur (Fig. 2). These regional differences in precipitation will impact soil water availability in rainfed agriculture, especially with the decrease in summer precipitation over the US and the agricultural region of Canada.

One important aspect of climate change with significance for agriculture is the potential impact, not only on the mean values of temperature and precipitation, but also on the frequency and severity of meteorological events within the growing season. Mearns et al. (1984) showed that relatively small changes in mean temperature can lead to large increases in the frequency of extreme events. Mearns et al. (1995) observed that in the Central Plains, a frequency decrease was the major change along with change in intensity. Gutowski et al. (2007) found that high intensity precipitation would constitute a larger fraction of the total precipitation under scenarios of global warming. These observations were found to be evident for all regions and seasons. Rind et al. (1990) suggested that both drought and floods may intensify with climate change. The change in probability of drought may increase more than would be expected due a reduction in mean precipitation and conversely, increases in floods or extremely wet portions of the year may be larger than expected from the increase in mean precipitation. Shifts in the intensity of storms have implications for availability of soil water to the crop because intense storms often lead to runoff rather than infiltration into the soil. The probability of drought will increase because the reduction in rainfall will be linked with an increase in potential evapotranspiration, which will exaggerate the effect of a reduction in precipitation. This characteristic of climate change has to be considered in evaluation of the potential impacts on agriculture or agroecosystems. Wang (2005) observed, based on the use of 15 global climate models, in the primary agricultural areas of the world there would be potential drought occurring over the next 50-100 years. The only consistent wet areas predicted from this ensemble of models were the northern middle and high latitudes and this was limited to the non-growing season period. This is similar to the analysis of Tao et al. (2003) for China in which they found that rainfed crops in the north China Plain and

northeast China would have challenges induced by soil moisture deficit and decreases in precipitation. Kim (2005) observed that future trends in precipitation induced by warming would lead to increased cold-season precipitation and increase the rainfall-portion of total precipitation in Sierra Nevada river basins in the western US. Dai (2006) evaluated the impact of surface air temperature, dewpoint temperature, and air pressure from around the world on specific humidity and relative humidity. He found that the spatial patterns of specific humidity were controlled by surface temperature. This change in specific humidity will impact the water vapor of the atmosphere and have a large impact on the potential evapotranspiration of agricultural areas. There are assumptions that increasing temperatures would benefit plant growth; however, a recent report by Zhao and Running (2010) suggest positive temperature effects were offset by the occurrence of drought during the 2000-2009 period. This decade was selected because it has been the warmest in recorded history with the concurrent expectation for an increase in the global net primary productivity. What was observed in the analysis was actually a decrease in net primary productivity because of the large-scale droughts around the world. One of their conclusions central to the discussion about climate impacts on biofuel production is increasing trends for drought around the world could intensify competition between food demand and biofuel production (Zhao and Running, 2010). The shifting precipitation patterns leading to increased uncertainty in soil water supplies, especially during the growing season, could impose a major limitation on plant growth and potential harvestable yield.

An overlooked component in the climate change discussion and important to plant growth is solar radiation. The projections regarding changes in precipitation in water vapor and cloud cover will increase contributing to a decrease in incoming solar radiation. Stanhill and Cohen (2001) evaluated the change in solar radiation and found for the past 50 years a reduction of

2.7% per decade with the current totals now being reduced 20 W m^{-2} reducing the daily total solar radiation values over the past 10 years across the central United States to 25.5 MJ m^{-2} day^{-1} from 26.3 MJ m^{-2} day^{-1}. They referred to this phenomenon as "global dimming." Changes in solar radiation would directly impact crop water balance and evapotranspiration of crops with less effect on crop productivity because of other factors limiting productivity (e.g., water, temperature, nutrients, and mutual shading within canopies). Evaluation of the impacts of a changing climate on plant production has to include an evaluation of a number of factors affecting plant growth.

Climate Impacts on Plant Growth

Climate change will directly impact plant growth and the effects of CO_2 and temperature have been summarized by Hatfield et al. (2008). There are some general statements which can be made about the climate change impacts. Rising CO_2 levels in the atmosphere will increase plant growth of C_3 species, while the effect in C_4 species will be rather small with the expectation that increasing CO_2 will also cause plants to become more water use efficient. This latter response will help offset some of the potential limitations caused by the increased probability of drought during the growing season. The improvement in water use efficiency is a direct result from reduced stomatal conductance and reduced transpiration relative to CO_2 uptake. An example of an experiment designed to evaluate this effect was reported by Bernacchi et al. (2007). They observed water use from soybean at elevated CO_2 levels in the free air carbon dioxide enrichment (FACE) plots with adequate soil water was less compared to control plots at ambient CO_2. When the control plots exhausted their water supply water use declined. However, in the elevated-CO_2 plots the stomata remained open for an additional six days and the plants continued to transpire. This allowed these plants to continue to photosynthesize and grow, while the control

plants ceased growth. Under rain-fed agriculture, which often experiences periods of water deficit, the net impact of elevated concentrations of CO_2 would be to enable conservation of soil water, buffering crop growth during periods of abiotic stress . This would enhance potential production even under periods of moderate drought, which would enable continued production of biofuels and overall would be a positive impact of rising CO_2 levels.

Rising temperatures will impact plant growth at multiple levels during the growing season. The review and synthesis by Hatfield et al. (2008) summarized the temperature responses for the major crop species and among these crops, maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L.) have potential as biofuel crops because of their large amount of grain or biomass residue. Each crop species responds differently to temperature throughout their life cycles with the vegetative period of growth having a higher temperature optimum than the reproductive stage. For example, in maize the maximum is at 37.0°C and minimum temperature is 8.0°C with an optimum near 34.0°C, while in the reproductive stage the minimum remains at 8.0°C and the optimum decreases to 22.0°C. Sorghum has very similar temperature responses as maize with an optimum reproductive temperature of 25.0°C. Exposure to higher temperatures during vegetative growth causes growth to progress at its fastest rate. Above the optimum, growth rates slow and cease when plants are exposed to their maximum temperature. Vegetative development (node and leaf appearance rate) will accelerate as temperatures increase up to the species optimum temperature. The projected increase in temperatures over the next 30-50 years will cause more rapid rate of plant development (Brown et al., 2000, Hatfield et al., 2008).

In both maize and sorghum, exposure to higher temperatures will cause faster rate of development and this doesn't translate into maximum production because shorter life cycle creates smaller plants, shortened reproductive duration, and reduced yield potential because of

reduced light interception during the growing season. Yields will be impacted when temperatures fall below or above specific thresholds at critical times during development.

One of the critical phenological stages for high temperature impacts is the reproductive stage because of the effect on pollen viability, fertilization, and grain or fruit formation. Yield potential will be affected by chronic exposures to high temperatures during the pollination stage of initial grain or fruit set. Temperature extremes during the reproductive stage of development can produce some of the largest impacts on crop production. The projection for increased high temperature extremes during the growing season will potentially impact yield from a three-fold effect. The first effect will be due to temperature stress alone causing reduced pollen viability and potential grain set and this coupled with reduced growth will lead to decreased yield. If we assume that harvest index (grain/stover production) is fairly constant then a reduction in vegetative growth will translate into reduced grain yield. The second effect would be exposure to high temperature extremes during the pollen stage limiting the potential grain set. The final effect from warming temperature, especially during the reproductive stage, is to decrease the length of grain-filling period through a more rapid grain-fill leading to smaller grain-size. The projected increase in minimum temperatures (Karl et al., 2009) will cause the grain-filling period to be shortened (Hatfield et al., 2008). An example of the evaluation of the temperature effect on maize yields is given by Muchow et al. (1990) who reported highest grain yields were from locations with relatively cool growing season mean temperatures (18.0 to 19.8°C at Grand Junction, CO), compared to warmer sites, e.g., Champaign, IL (21.5 to 24.0°C), or warm tropical sites (26.3 to 28.9°C). In a later study across a greater range of sites, Lobell and Field (2007) evaluated the effects of temperature and rainfall using records from 1961-2002 and found an 8.3% yield reduction per 1.0°C rise in temperature. Runge (1968) observed maize yields were

responsive to interactions of daily maximum temperature and rainfall 25 days prior and 15 days after anthesis. He found interactions between temperature and rainfall when rainfall was low (zero to 44 mm per 8 days), yield was reduced by 1.2 to 3.2% per 1.0°C rise. Conversely, when temperatures were warm (Tmax of 35°C), yield was reduced 9% per 25.4 mm decline in rainfall. In sorghum, maximum dry matter production and grain yield has been observed at 27.0(day)/22.0(night)°C compared to exposure to temperatures 3.0 or 6.0°C lower or 3.0 or 6.0°C warmer (Downs, 1972). Duration of grain filling decreases as temperature increases and reduces grain yield (Chowdury and Wardlaw, 1978; Prasad et al., 2006). In a recent analysis of temperature effects on maize, soybean [*Glycine max* (L.) Merr.] and cotton (*Gossypium hirsutum* L.), Schlenker and Roberts (2009) found temperatures above 29.0°C in maize reduced yields and the slope of yield decline above this temperature value was greater than the increase in yield observed up to this temperature threshold. They projected for these three crops a 30-46% decrease in yield for the slowest warming scenario and a 63-82% decrease under a more rapidly warming scenario. Kucharik and Serbin (2008) evaluated temperature and precipitation impacts on corn and soybean production in Wisconsin and concluded that for each additional degree of warming during the summer months corn yields would decrease by 13% and soybean by 16%. In their analysis they observed that potential increases in precipitation could offset the negative temperature impacts. These values are much larger than those projected by Hatfield et al. (2008); however, they show the potential implications of warming on crop production. Projected changes in both temperature and precipitation leading to more extreme events during the growing season will create a situation in which crop yields and also biomass production will decrease in C_4 crops like maize and sorghum. The interactions of temperature and precipitation on plant growth and exposure to conditions outside of the optimum temperature range and

decreased soil water availability will combine to have a negative impact on growth and grain yield.

Implications of Climate Change on Biofuel Production

Climate impacts crop production and as an example, maize biomass production is presented for Iowa and Georgia and sorghum for silage production in Kansas to demonstrate variation in production over time. Data on corn stover production were derived from the statewide average grain yields available from the National Agricultural Statistics Service (NASS at www.nass.usda.gov/Quickstats) and converted to stover yield assuming a harvest index of 0.5. Hatfield (2010) demonstrated that these observations provide a valuable source of information to evaluate the effects of climate on crop production. In the Iowa data, there are some important observations emerging from the records typical of the Corn Belt (Fig. 3). First, there is a continual upward trend in stover production with amounts more than doubling over the past 60 years and the expectation for continued increases in the future. Second, there is a period in the record from 1970 through 1995 exhibiting large variation among years with the variation related to more variation in annual rainfall during this period. The projected climate scenarios for the next 40-50 years are not different than this period with more variable precipitation and interannual variation within the growing season. As shown in Fig. 2 there is a projected decrease in summer precipitation across most of the United States which will increase the potential likelihood of drought occurrences. These projections are confirmed by a recent analysis of Mishra and Cherkauer (2010) and their findings that maize yields were correlated with meteorological drought and maximum daily temperature during the grain filling period. With the re-emergence of variation in growing season precipitation coupled with the increasing

temperatures, leading to greater water use by the crop, then the expectation across the Corn Belt will be enhanced variation in corn grain and stover production among years.

Analysis of corn production trends from Georgia, typical of the Southeastern United States, show similar patterns to those in Iowa (Fig. 4). There has been a steady progression upwards in corn grain and stover production and these values represent a combination of irrigated and rainfed production systems. Production levels are lower in Georgia than in Iowa; however, the effect of climate on stover yields exists throughout the entire record due mainly to precipitation variation during the growing season (Fig. 4). In both states, decreases in precipitation during the June-August period below the normal amounts were the most significant in affecting production. Decreases in stover production often exceed 30% from the trend line for the record. This same magnitude of reduction is found in the Iowa data as well indicating climate impacts cause significant reductions in corn production. Sorghum for silage production data for Kansas were selected as being representative of a forage crop and there was a large variation in these production values over time (Fig. 5). There are some significant differences in the yield trends lines for the sorghum data compared to the corn. First, there is no increasing trend in yields over the 60 years of data. Second, the variation in production among years shows over a 30% decrease in yield with one-third of the years showing a negative yield response. Precipitation is more variable in Kansas compared to either Iowa or Georgia; however, the magnitude of this variation may be indicative of the potential increasing variation in precipitation under future climate scenarios. Climate variation does affect production and the observations by Hatfield (2010) and Zhao and Running (2010) reveal that variation in growing season precipitation is the primary variable affecting production. The projections for increased variation in annual precipitation and

overall declines in the growing season precipitation amounts will further exaggerate annual variation in production.

Two other crops are considered as potential energy crops, Switchgrass (*Panicum virgatum* L.) and Miscanthus (*Miscanthus* x giganteus). Both of these are warm season perennial grass species with higher optimum temperatures than corn. Beale and Long (1995) evaluated the response of Miscanthus to more northern latitudes and cooler climates and found the growth was not affected. This would suggest that this crop would be highly adapted to a wide range of climates. Brown et al. (2000) used the erosion productivity impact calculator (EPIC) model to simulate the impact of changing climate on switchgrass, corn, sorghum, winter wheat, and soybean and found that increasing temperatures decreased yields of all crops except switchgrass. They observed the warmer temperatures increased heat stress on the grain crops and hastened crop maturity; however, for switchgrass the lengthening of the growing season and reduced cold stress contributed to the positive response to a warming climate. There are no long-term data sets available to evaluate the impacts of variable precipitation on Miscanthus or swtichgrass and some evaluations on water use conducted in Illinois demonstrate water use was higher for both of these crops compared to maize (Hickman et al., 2010). VanLoocke et al. (2010) observed that Miscanthus had a higher water use rate and depleted soil water more than maize. Both of these studies show that water use by these two crops are higher than the traditional grain crops in the Midwest and variation in precipitation would create variations in production. However, given the higher water use rates the impact of increased variation in precipitation may create larger interannual variations in production compared to the corn and sorghum production data shown in Figs. 3, 4, and 5.

Production of annual and perennial crops offers a potential source of biofuels; however, increased variability in climate over the next 50 years will increase the variability in annual production. This variation will lead to uncertainty in the supply of biomass for energy and also continue to create a situation of the food versus fuel debate in the most appropriate use of the land resources. There are potential adaptation strategies which could be implemented to alleviate some of the potential negative impacts including alteration in planting date, shifting cultivars, greater mix of genetic material to reduce risk, implementation of soil management practices which enhance water conservation and availability to the growing crop, and shifts in the mix of species to take advantage of the warming climate. These have be evaluated for these production systems, but, the information exists from research on dryland farming systems and research conducted during the 1960-1980's in terms in increasing production in water-limited and more arid climates. The future is not bleak; however, there are some challenges to be addressed to ensure we have an adequate balance of food, feed, fiber, and fuel.

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Figures

Figure 1. Changes in annual precipitation over the United States from 1958 to 2008. (adapted from Karl et al., 2009).

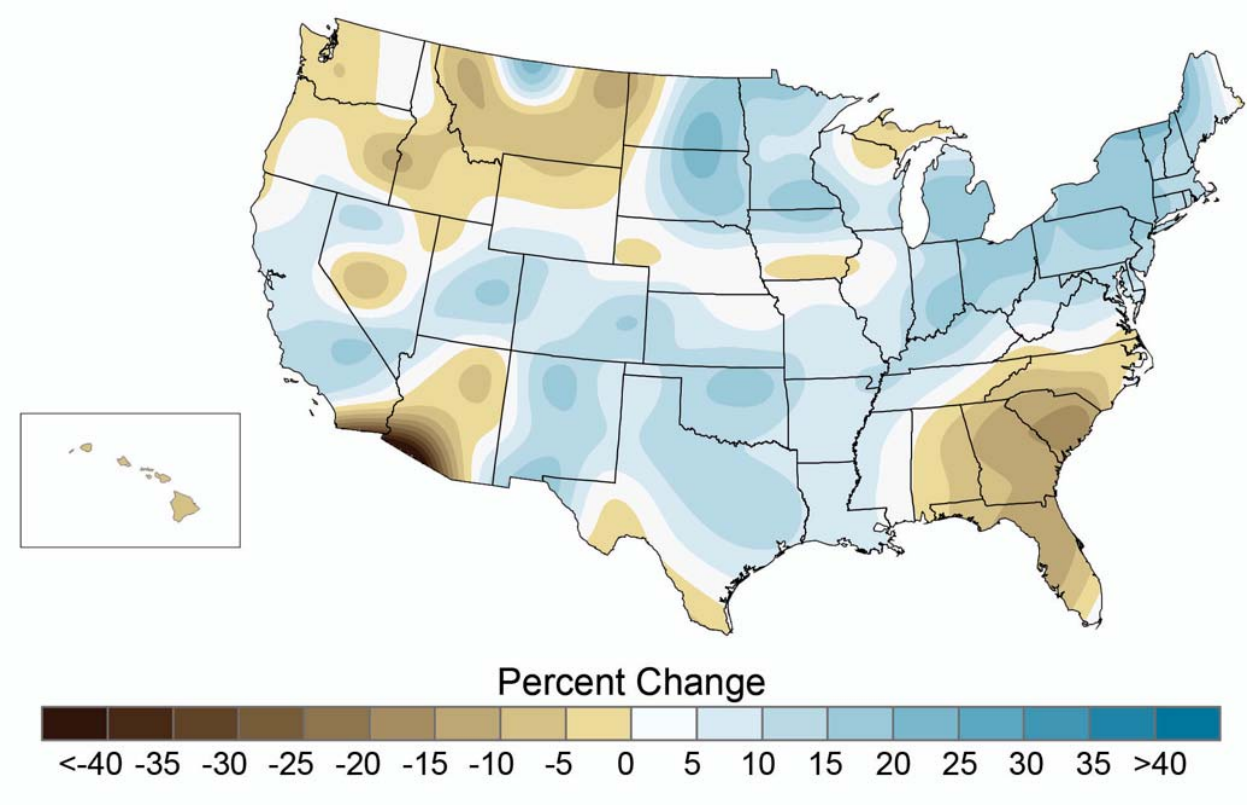
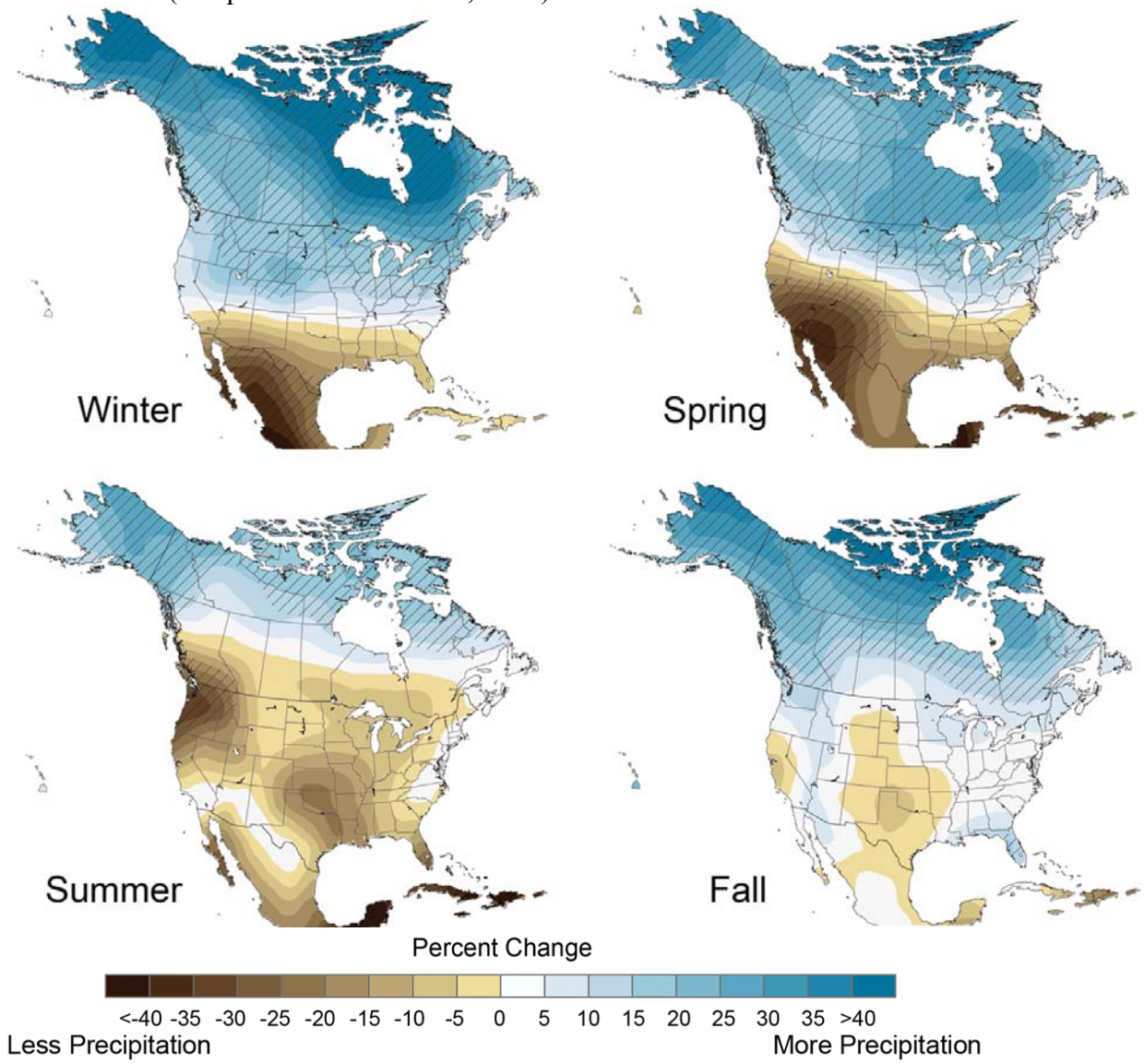


Figure 2. Projected regional changes in precipitation across North America for the period of 2080 to 2099. (Adapted from Karl et al., 2009).



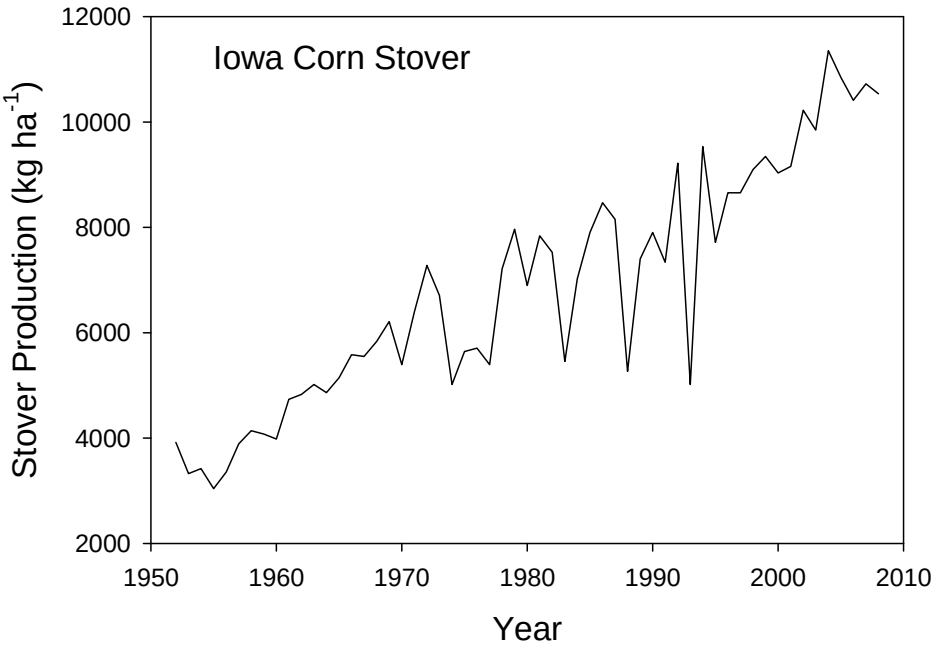


Figure 3. Variation in corn stover production derived from annual corn grain yields across Iowa from 1950 – 2008. (Grain yield data extracted from NASS Quickstats, www.nass.usda.gov)

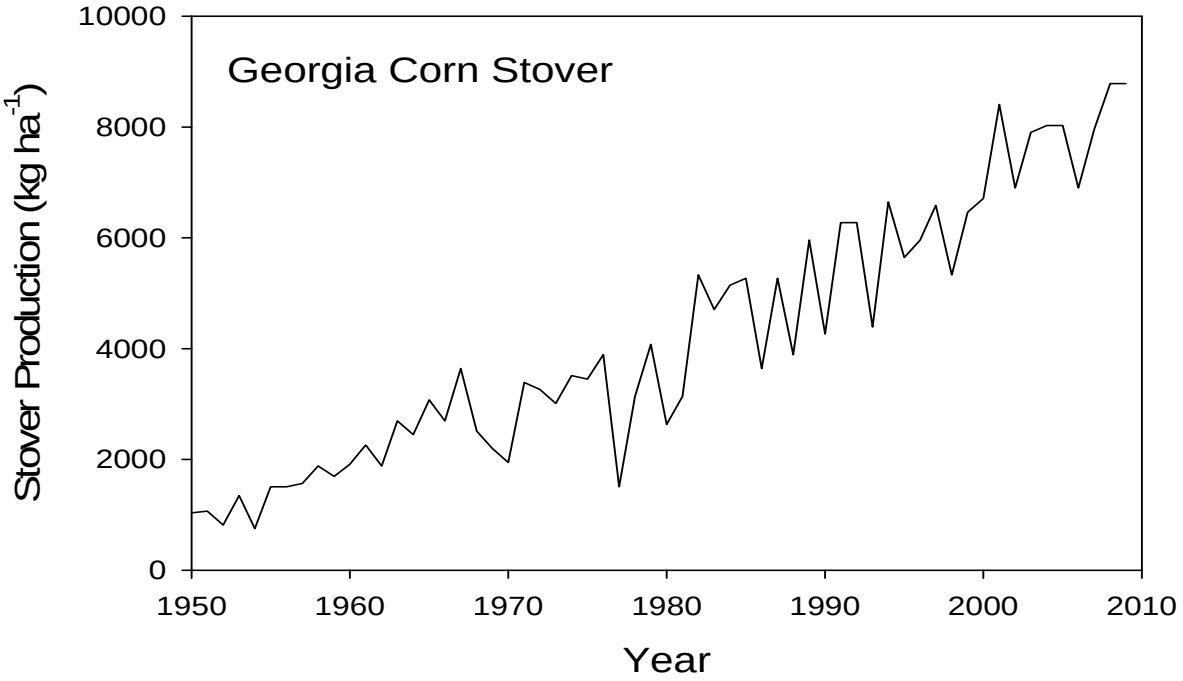


Figure 4. Variation in corn stover production derived from annual corn grain yields across Georgia from 1950 – 2008. (Grain yield data extracted from NASS Quickstats, www.nass.usda.gov)

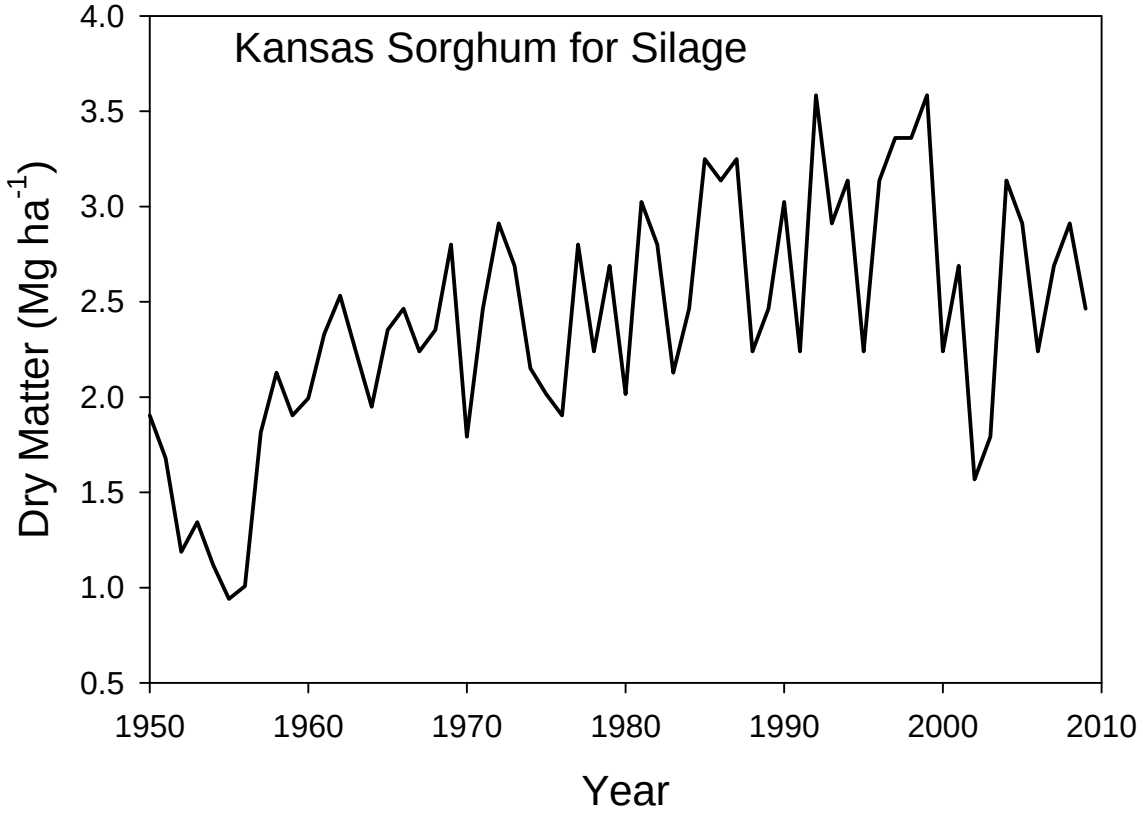


Figure 5. Variation in sorghum for silage production for Kansas from 1950 – 2009. (Production data extracted from NASS Quickstats, www.nass.usda.gov)