Chapter 6

Climate Change Impacts on Corn Phenology and Productivity

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Additional information is available at the end of the chapter

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Abstract

Global climate is changing and will impact future production of all food and feed crops. Corn is no exception and to ensure a future supply we must begin to understand how climate impacts both the phenological development of corn and the productivity. Temperature and precipitation are the two climate factors that will have a major benefit on corn phenology and productivity. The warming climate will accelerate the phenological development because the number of thermal units required for leaf appearance is relatively constant in the vegetative stage. Productivity of corn is reduced when extreme temperature events occur during pollination and is further exaggerated when there are water deficits at pollination. During the grain-filling period, warm temperatures above the upper threshold cause a reduction in yield. Model estimates suggest that for every 1°C increase in temperature there is nearly a 10% yield reduction. To meet world demand, new adaptation practices are needed to provide water to the growing crop and avoid extreme temperature events during the growing season. Climate change will continue to affect corn production and understanding these effects will help determine where future production areas exist and innovative adaptation practices to benefit yield stability could be utilized.

Keywords: agroclimatic indices, simulation models, G × E × M interactions

1. Introduction

Corn (*Zea mays* L.) is grown throughout the world and as such is subject to a wide variety of climates and potential scenarios of climate change. Production area continues to increase in response to the increased demand for corn grain and the production per unit area (yield) has continued to increase due to enhanced technology (**Figure 1**). What is imperative to stability

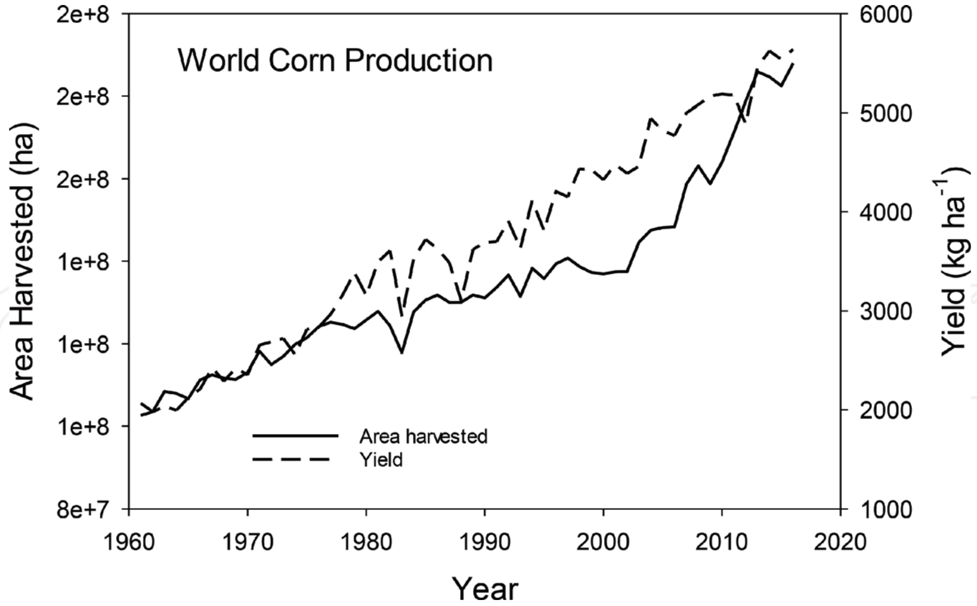

Figure 1. World corn yield and area harvested since 1960 (data obtained from FAO stat, http://www.fao.org/faostat/en, downloaded March 8, 2018).

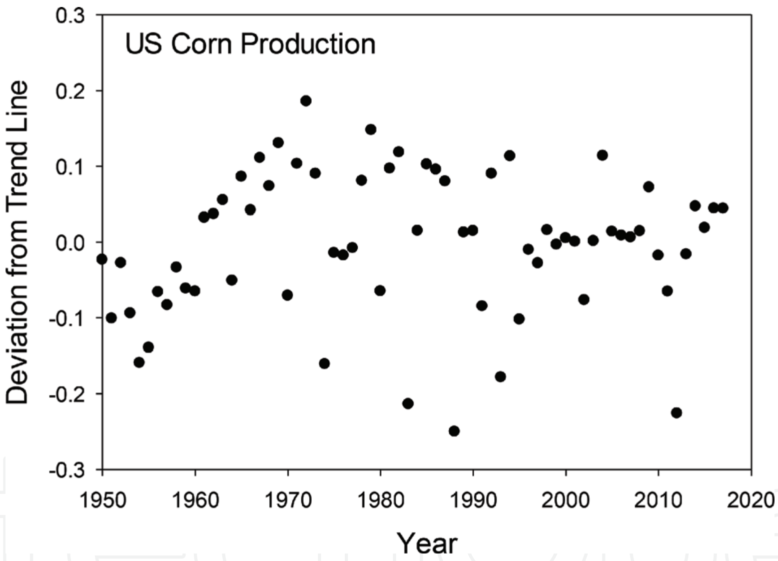

Figure 2. Deviations from the yield trend line for corn production in the United States from 1950 to 2017. (data obtained from the National Agricultural Statistics Service, www.nass.usda.gov, accessed March 8, 2018).

and increases in future production is understanding how climate change will impact this trend in corn production and the areas of the world where corn is produced. Corn is a grain crop with both food and feed uses and variation in production at the local scale can have major impact on local economies and local food supplies as well as world food security.

The trend line for corn yield has shown a steady increase and a small amount of variation among the years; however, at the local scale is where the impacts of seasonal weather and trends in climate become more noticeable. Across the United States, there have been large deviations from the trend line in years in which weather events have caused yield reductions

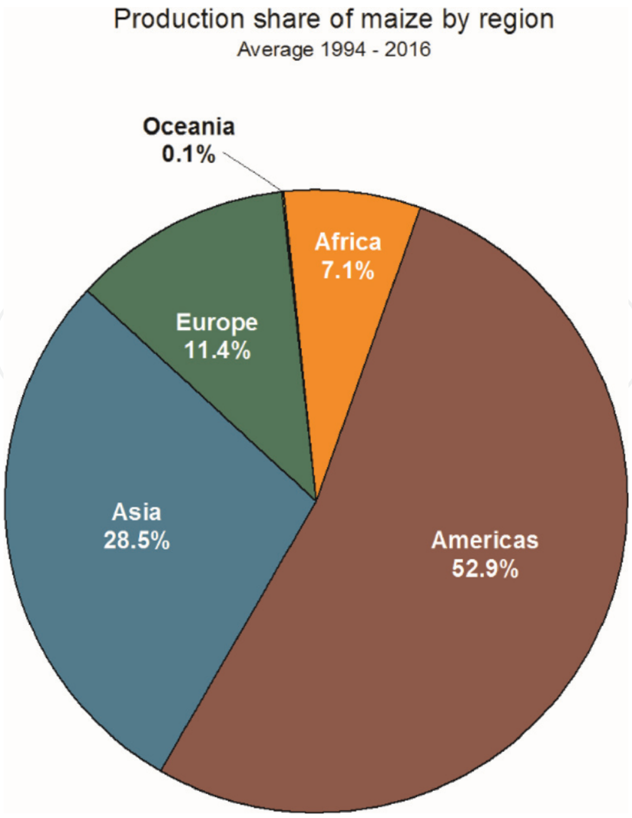

Figure 3. World corn production by region. (data from FAOSTAT, downloaded March 15, 2018).

(**Figure 2**). Throughout this chapter, we will focus on the impacts of climate on corn phenology and production to provide an understanding of the potential for adaptation strategies. In this chapter we will focus on three components critical to corn production: the changing climate, impact of climate on corn phenology and phenological models, and impact of climate on corn productivity.

The production regions for corn show the dominant areas in the Americas followed by Asia accounted for 81% of the world's corn production (**Figure 3**). Climate impacts in the Americas and China will dominate the effects on future corn production.

2. Projections of climate change

Projections of climate change are a result of a combined set of simulation models using various scenarios of changes in carbon dioxide (CO_2) concentrations and the associated forcing functions [1]. The current CO_2 concentrations are at nearly 400 ppm in 2018 and are projected to increase to a range of 794–1142 ppm by 2100 without any abatement scenarios [1]. The result of these efforts can be summarized as [1, 2]:

1. Global mean temperatures will continue to increase throughout the twenty-first century if CO_2 concentrations continue to increase and under the highest emission scenario would range from 2.6 to 4.8°C.

2. These temperatures changes will not be uniform across regions with increases over land surfaces being larger than over the oceans.

3. As the global temperatures increase there will be more hot extremes and fewer cold extremes at both daily and seasonal time scales.

4. Precipitation will increase with increases in global mean surface temperature and could increase 1 to 3% $°C^{-1}$; however, there will be substantial spatial variation in these changes.

5. The water holding capacity of air increases by 7% $°C^{-1}$. The air can take up more water, and water vapor inclines. That leads to higher intensity of precipitation, i.e. higher amount of rainfall per rain event.

6. Annual surface evaporation will increase as the temperatures increases; however, over land, evaporation will be linked to precipitation.

These factors will affect corn growth and productivity and this chapter is directed toward showing how these changes in climate will potentially affect corn production in the future. A general summary of climate impacts on crops was prepared by Hatfield et al. [3] and reveal for corn that temperature and precipitation are the two critical factors. Since corn is a C4 plant, the response to increasing CO_2 will be minimal. Leakey et al. [4] found that leaf photosynthetic response was 3% to a doubling of CO_2 concentrations while total biomass and grain yield increased by 4%. They did observe that leaf stomatal conductance was decreased by 34% under these same experiments. These differences in physiological activity due to increased CO_2 are small compared to C3 species and will not the most evident response to the changing climate. Therefore, in this chapter we will focus on temperature and precipitation impacts on corn.

3. Phenology of corn

The phenology of corn has been described as the appearance of leaves or leaf collars during the vegetative stage and accumulation of material in the grain during the reproductive stage. The developmental stages of corn has been recently described by Abendroth et al. [5] and similar guidelines are used to quantify the phenological stage of corn during the growth cycle. What is important for assessing the effect of climate on corn is to explore what role climate variables have on corn phenology. The most critical variable in phenological development is temperature and each plant has a specific range of temperatures for growth as defined as the upper and lower limit (threshold) and an optimum [3]. For corn during the vegetative stage this has been identified as 8 to 38°C with an optimum of 34°C [6, 7] while the range for the reproductive stage is 8–30°C [8]. Typically, the lower temperature limit in growth models has assumed to be 10°C. Survival of pollen are sensitive to temperature, e.g., temperatures exceeding 35°C have been proven detrimental to pollen viability [9, 10]. There is a strong interaction of temperature with vapor pressure deficit and the viability in the time of movement from the tassel to the silk has been shown to decrease with decreasing moisture content [11]. These results would suggest that as the temperature increases and vapor pressure deficit increases that disruption of the pollination process could become more likely especially with the potential for more extreme temperature events. Quantifying the impact of episodes of temperature extremes on pollen viability and the disruption of reproductive processes will become more important with the projection that extreme temperature events will increase under climate change (Tebabldi et al. [12]). These temperature ranges and the potential for extreme events will become important for corn growth and production because of the projection that temperatures will increase in the future.

The relationship of corn phenology to temperature has been described through the use of growing degree days with a growing degree day (GDD) calculated as $(T_{max} + T_{min})/2 - T_{base}$, where T_{max} is the maximum daily temperature, T_{min} is the daily minimum temperature and T_{base} is the temperature at which growth stops. Kumudini et al. [13] evaluated eight different thermal models for the estimation of corn phenological development. These thermal models were classified into empirical linear typical of the GDD model first shown by Gilmore and Rogers [14] with the most robust model having a T_{base} of 10°C and an optimum of 30°C. Another class of thermal models is the empirical nonlinear model described by Brown and Bootsma [15] where the following relationships were used to estimate crop heat units (CHU): if T_{min} < 4.4°C then T_{min} = 4.4°C to derive $CHU_{min} = 1.8(T_{min} - 4.4°C)$; if T_{max} < 10°C then T_{max} = 10°C; to derive $CHU_{max} = 3.33(T_{max} - 10°C) - 0.084(T_{max} - 10°C)^2$ and $CHU = (CHU_{max} + CHU_{min})/2$. Stewart et al. [16] used a non-linear empirical model and separated the vegetative and reproductive stages of growth with different functions. The third class of thermal models can be classified as the process-based models similar to the thermal functions used in Agricultural Production Systems sIMulator (APSIM) as described by Wilson et al. [17] which are based on estimates of air temperature at 3 hour intervals throughout the day and given as: if T < 0°C then T = 0°C and if T > 44°C then T = 44°C and calculated for different temperature ranges as 0°C = < T < 10°C: IR = T(10/18°C); 18°C = < T < 34°C: IR = T – 8°C; and 34°C = < T < 44°C: IR = 26°C – (T – 34°C)2.6 and thermal units are given as ∑(IR/8), where IR = instantaneous rates or measurements. In comparing these different approaches, Kumudini et al. [13] found that the precision in terms of goodness of fit was calendar days < empirical linear < process-based < empirical non-linear.

An application of the GDD approach was developed by Neild and Richman [18] where they combined thermal units with precipitation in an agroclimatic index to determine where different corn hybrids could be grown around the world. Currently, this type of model has been replaced with simulation models similar to APSIM [19] to determine climate impacts on corn growth and production. If the thermal units per leaf appearance rate is constant for the vegetative stage of growth then as the temperature increases there will be a more rapid accumulation of leaves in the crop. This effect as observed by Hatfield [20] and Hatfield and Prueger [21] for corn grown under climatic normal (1980–2010) for Ames, Iowa and normal +4°C temperatures throughout the complete growing season for three different corn hybrids. There was no difference in the total number of leaf collars and cumulative leaf area between temperature regimes; however, there was a large difference in yield with the higher temperatures greatly reducing grain yield (**Figure 4**). Analysis revealed there was no difference in the GDD's for leaf collar appearance between the two temperature regimes suggesting that as temperatures increase there will be a more rapid rate of advancement in the phenological

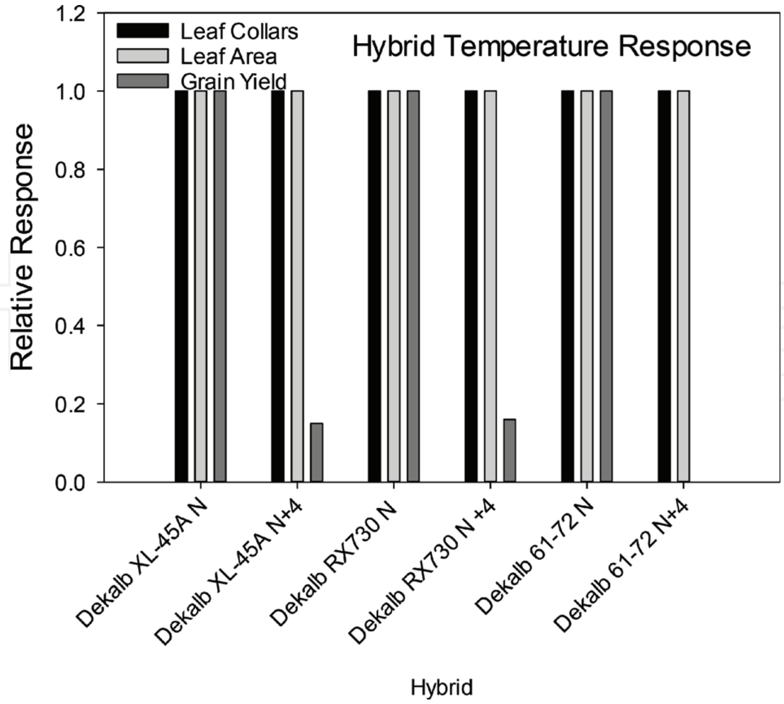

Figure 4. Differences in total leaf collars, cumulative leaf area, and grain yield of three corn hybrids grown under normal Ames, Iowa temperatures and normal +4°C temperatures. (data redrawn from [20]).

development with no effect on the size of the corn plant at the end of the vegetative stage. There was a large difference in grain yield between temperature regimes with a faster rate of maturity with a subsequent reduction in grain production.

4. Corn productivity in response to climate

Corn productivity relative to climate is a function of both temperature and precipitation. Effects of increased temperatures have shown a large degree of variation with projections of reduced production by less than 5% with temperature increases of 1°C [3] to over 50% with 4°C increases [22]. Productivity of corn is affected by temperatures exceeding 35° C during pollination due to dehydration of the pollen [3]. Controlled environment studies have confirmed the effect of high temperatures on corn with temperatures greater than or equal to 3°C above normal temperatures showing maize yield reductions of over 50% in grain yield [20, 21]. They observed an increased rate of phenology with increased temperatures; however, the largest effect on productivity was attributed to the increase in minimum temperatures during the grain-filling period. Field studies on corn have shown under field conditions yield reductions from 13 to 88% due to increased temperature 6°C above normal temperatures [23]. The negative effects of high temperatures during the grain-filling period were attributed to pollen survivability and the efficiency of the grain-filling process. Increasing temperatures likely to be experienced under climate change demonstrate several negative effects plant growth and phenology. Lizaso et al. [24] recorded a reduction of corn yield under field and controlled conditions owing to reduced pollen viability as impacted by increased temperatures. A critical knowledge gap under future climate scenarios will be to evaluate the interaction of high temperature and increased humidity on pollen survivability and the efficiency of the pollination process. Lobell and Field [25] found maize yields decreased 8.3% per 1°C rise without any additional effect due to water stress which was confirmed by Mishra and Cherkauer [26] for Midwest corn grain yields. Challinor et al. [27] compiled a meta-analysis of over 1700 published simulations for wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), and corn. They found that without implementing adaptation strategies there would be a loss in yield in both temperate and tropical regions with only 2°C of warming. They also found that adaptation practices could increase simulated yields by 7–15% with this same temperature increase; however, the practices were more effective in wheat and rice than for corn. There was consensus among the simulation models that yield decreases were be greater in the second half of the century with the greater declines in the tropical areas compared to the temperate regions. They estimated that corn yields would decrease by nearly 15% in temperate regions with a 4°C increase and no adaptation but showed no decrease with adaptation practices [27].

Temperature and precipitation interact to affect corn productivity. Short-term water deficits and drought reduce growth and grain yield and are often the largest cause of crop losses. In the United States, drought was related to 41% of crop losses, while excess water was attributed to 16% of the yield loss [28]. Drought stress during the early and middle reproductive stages affected grain yields and these phenological stages were found to be the most sensitive to water stress [29]. Increases in spring precipitation can cause yield reductions due to aeration stress caused by flooded soils; however, drought stress remained the primary factor linked with reduced grain production [29]. In rainfed environments where corn is primarily grown, temperature and precipitation changes under climate change will negatively impact grain production and these interactions need to be more fully understood. In an analysis of wheat production in Europe, Semenov et al. [30], stated that understanding of the effects of higher temperatures and drought stresses during the booting and flowering periods would potentially lead to adaptation practices with the potential to reduce losses in grain numbers and grain weight. With both short-term water stress and drought as major factors affecting grain yield, improved water availability through more extensive root system and changes in root architecture would benefit yield stability [31]. The excess soil moisture in the root zone will require improved soil structure to facilitate gas exchange between the root system and the atmosphere [32]. The impact of precipitation is a combination of the precipitation amount and the soil water holding capacity. This was illustrated in an analysis by Egli and Hatfield [33] where they found average county level corn yields were a function of the soils ability to supply water.

Evaluation of corn yield response to climate is complex because of the interactions of the impacts of temperature and precipitation. To provide a more robust framework for evaluating yield response the utilization of the yield gap as the difference between potential yield and actual yield has been utilized ([34]; van Bussel et al. [35]). This concept has been discussed and utilized for several decades but recently has been extended to create a yield gap atlas for the world. The yield gap approach allows for a quantitative assessment of the ability of the crop to achieve its potential yield and the inability of closing the yield gap can often be ascribed to climatic stress. Potential yield has been defined as "the yield of a cultivar when grown in environments to which it is adapted; with nutrients and water not limiting; and with pests, diseases, weeds, and other stresses effectively controlled" [36]. Potential yield (Y_P) is an expression of the ability of a crop canopy to convert solar radiation into dry matter with no stress during the growth cycle and radiation use efficiency can be used as a measure of this efficiency [37]. The goal of agronomic science is the evaluate practices and increasing the farmer yield (Y_F) may prove to be more fruitful than increasing potential yield (Y_P) ([38]; Lobell et al. [39]. Utilizing the yield gap approach provides a framework for evaluating the factors which affect crop yields and the phenological stage which these factors are having the most significant impact during the growing season. These studies are not simple analyses, because of the interactions of multiple factors affecting yield, and Sinclair and Ruffy [40] argue that nitrogen and water limit crop yield more than plant genetics and should be considered as the primary factors limiting yield. Understanding the yield gap requires being able to quantify both potential and actual yield and comparison among studies is often limited by the lack of consistent data and to advance our understanding of yield gaps will require standardized method for yield comparisons [41]. Fischer et al. [41] introduced attainable yield (Y_A) as a metric between Y_F and Y_P defined as the yield achieved by a producer under near optimum weather and management inputs. Hatfield et al. [42] utilized this approach on county level corn yields in the Midwest United States and defined the attainable yield as the years with the highest yield in the long-term record as illustrated in **Figure 5**. The values for attainable yield are derived by statistically fitting a line through the frontier of the yield observations and then computing the yield gap as the difference between the attainable and actual observed yield for each year. In this analysis, data from 1950 through the present are used because this represents

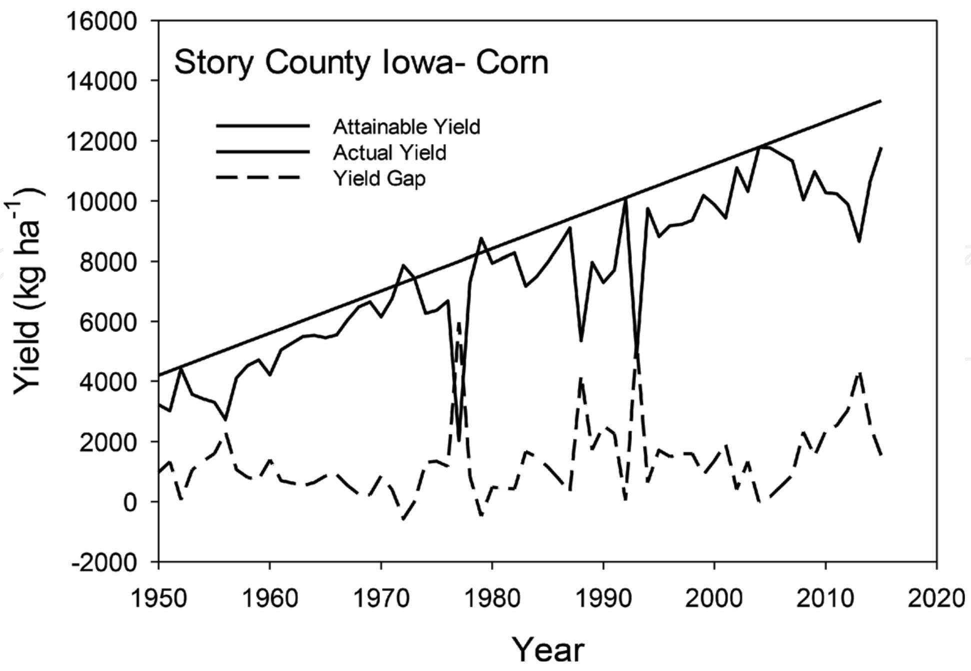

Figure 5. Yield gap analysis for Story County, Iowa, USA using attainable yields derived from annual production values. (data obtained from the National Agricultural Statistics Service, www.nass.usda.gov, accessed March 8, 2018).

the period of time with corn hybrids and enhanced production technology. This approach has been used for different crops and regions of the world to obtain yield gaps.

Hatfield et al. [42] utilized the yield gap approach for the Midwestern US to quantify the effects of climate variability on corn production and found three dominant climatic factors related to the yield gap. These were July maximum temperatures, August minimum temperatures, and July–August total precipitation. Yield gaps increased when July maximum temperatures exceeded 32°C, August minimum temperatures exceeded 20°C, and July–August precipitation totals decreased below 150 mm. The physiological reasons for these variables are related to the disruption of pollination (July temperatures), increased rate of senescence and reduced efficiency of grain-fill (August minimum temperatures), and water deficits during a period of the year with high crop water requirements (July–August precipitation). These relationships were observed for each county in the Midwest and utilized to project the impact of future climate change on the yield gap on corn production. They found that with the trends in temperature for the summer in the Midwest US that yield gaps would exceed 50% by the year 2075 in the southern portion of the Corn Belt. There were some counties in the Midwest in which excess moisture in the spring was related to the yield gap but these relationships were not robust enough for use in projections of future climates. The yield gap framework provides a robust method for assessing the impact of climate on yield variation over time and when combined with efforts similar to those used by Challinor et al. [27] could be used to quantify the impact of adaptation practices.

5. Agroclimatic indices to define corn production regions

Corn is produced around the world and within these areas there may be shifts in production areas due to the changing climate. Green et al. [43] have quantified the changes in the US Corn Belt and provided a geographic analysis to depict these shifts in distribution. Development and utilization of agroclimatic indices has value in being able to assess these shifts because they are related to temperature and precipitation. Neild and Richman [18] were among the first to use the GDD concept to define potential differences among corn hybrids. Development of tools to define where crops can be produced is critical to understand crop distribution and productivity [44]. Estimation of crop distribution within arable areas is necessary to determine whether a species can thrive in an agroclimatic zone and will become more critical with the projected increases in temperature. Zomer et al. [45] extended this concept to demonstrate how climate zones could be used to evaluate technologies that would enhance the ability of management practices to offset the impacts of climate change on crop production. There have continued to be advances in the development of agroclimatic indices to evaluate the suitability of a location for a particular crop since Neild and Richman [18]. Siddons et al. [46] cautioned that development of robust agroclimatic indices requires observations collected over long time periods and extensive observations from experimental locations. There has been an evolution in agroclimatic indices to include more factors affecting plant growth and development to derive values that characterize the environment and the potential for crop production. Typical factors are: average daily minimum temperatures below 0°C; daily mean temperature to estimate crop development rates; average daily maximum temperature above 35°C to estimate exposure to heat stress, especially during pollination; average daily soil water availability (precipitation–reference evapotranspiration (ET)); and length of specific phenological periods to estimate the effects of changing phenological development on biomass accumulation and crop yield [47]. They found a positive relationship between productivity and their suitability index [47]. This approach is a refinement of the effort by Neild and Richman [18] and incorporated more factors to more link crop physiological responses with phenological development.

Agroclimatic zones are a combination of factors affecting plant growth to evaluate the potential for grain or forage crop production (e.g., [18, 44, 48–51]). The form of the index depends upon the assumption of the factors limiting growth. Soil water availability is often the determining factor in crop production in all ecosystems and the application has ranged from determination of irrigation water requirements or potential impacts on production caused by water deficits. Daccache et al. [49] incorporated soil water variability to evaluate the need for irrigation for potato (*Solanum tuberosum* L.) production in England and Wales. Their index was based on the potential soil moisture deficit (PSMD) index defined as:

$$PSMD_i = PSMD_{i-1} + ET_i - P_i \tag{1}$$

where $PSMD_i$ is the value in month i and $PSMD_{i-1}$ is the value for the previous month, ET_i is the reference ET for the current month calculated with the Penman-Monteith equation formulated by Allen et al. [52], and P_i the precipitation in the current month. They found increased variation in precipitation decreased potato production in an area currently suited for production, unless supplemental water was provide through irrigation. This type of analyses could be utilized to determine the need for supplemental irrigation to ensure crop production.

Another form of this type of framework was developed by Moeletsi and Walker [51] to quantify climate risk for corn production in South Africa. They based their index, Poone AgroClimatic Suitability Index (PACSI), on three climatic parameters; onset of rains, frost risk, and drought risk utilized a weighed distribution of climate parameters as

$$PASCI = O\ x\ 0.3 + FF\ x\ 0.3\ x\ WRSI\ x\ 0.4 \tag{2}$$

where O is the probability planting conditions are met, FF is the probability of a frost-free growing period, and the water requirements satisfaction index (WRSI). These indices require sufficient data over a long period of record to develop the probability of the different indices to develop reliable probability assessments [46]. An aspect of this index is the assessment of drought risk which is a complex interaction by soil water holding capacity and any change in the soil affecting water availability (Eq. 2).

Precipitation effects on crop productivity are defined by the occurrence of the water deficits in the soil profile which fail to meet the evaporative demand. Agroclimatic indices for arid and semiarid regions are often based on precipitation amounts adequate to exceed the ET rate at the time of planting in order to ensure crop establishment [18, 47–49, 51]. Moeletsi and Walker [51] evaluated soil water dynamics based on the WRSI to determine the potential to meet crop water requirements at any phenological stage as

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$$WR_i = PET_i \, x \, k_{ci} \tag{3}$$

where WR_i is the water requirements for a decadal period during growing season, PET_i is the potential ET during this decadal period, and k_{ci} the crop coefficient for this corresponding phenological period. For any decadal period during the growing season, the soil water balance can be used to estimate plant available water (WA_i) as

$$WA_i = Prec_i - SW_{i-1} \tag{4}$$

and $Prec_i$ is the precipitation in a given decadal period and SW_{i-1} is the profile soil water content for the previous decadal period. Soil water holding capacity (WHC) becomes a critical component of this method because available SW is a function of WHC. They computed the WRSI as

$$WRSI_i = WRSI_{i-1} - \frac{WD_i}{\sum_{i=1}^{end} WR} \tag{5}$$

with WD_i the water deficit for decadal period i, defined as

$$WD_i = WR_i - Prec_i - SW_{i-1} \; when \; WR_i > Prec_i + SW_{i-1} \tag{6}$$

Or

$$WD_i = 0 \; when \; WR_i = Prec_i + SW_{i-1} \tag{7}$$

In this process soil water in the profile is quantified as

$$SW_i = Prec_i + SW_{i-1} - WR_i \tag{8}$$

$$SW_i = WHC \; when \; SW_i = WHC \tag{9}$$

$$SW_i = 0 \; when \; SW_i = 0 \tag{10}$$

Using this methodology, Moeletsi and Walker [51] were able to evaluate the suitability for maize production for various planting dates with a correlation of 0.8 between the PACSI and grain yields.

Precipitation is changing in intensity and frequency, and directly affect WA_i (Eq. 3). Precipitation patterns are projected to increase in annual totals, with decreasing summer precipitation amounts over the US [1, 53]. If we link these precipitation patterns with the PACSI (Eq. 2), then corn production could become more variable among years because of soil water availability.

Utilization of agroclimatic indices as a tool for the assessment of climate impacts on corn production areas will provide a quantitative view of shifts in production areas but potential risks to production within areas where corn is currently produced. The continued development of these tools will benefit corn production because we can evaluate the potential role of management and genetic resources on increasing yield stability over time.

6. Simulation models to quantify climate effects

Simulation models have been extensively used to estimate the impact of a changing climate on productivity. In 2014, Challinor et al. [27] summarized 1700 published reports using simulation models and the number of papers has increased rapidly since that time. Simulation models provide the capability of assessing the potential impacts of the change in temperature and precipitation under a given CO_2 regime and often models using the different emission scenarios to determine the expected temperature and precipitation parameters which are then placed into crop simulation models [54, 55]. It has been found that an ensemble of crop models provides a more rigorous approach to estimating crop responses to climate. This is being conducted under the Agricultural Model Implementation and Improvement Project (AgMIP) framework as described by Rosenzweig et al. [56]. Bassu et al. [57] used this framework to compare 23 different corn models and found temperature decreased yield by approximately -0.5 Mg $ha^{-1}{}^{\circ}C^{-1}$ while doubling the CO_2 from 360 to 720 μmol mol^{-1} increased yield by 7.5% across all models and sites. They concluded that temperature increases would be the dominant factor affecting corn yields. Zhao et al. [58] summarized a number of published results and found for each 1°C increase, corn yields decreased by 7.4%. Jin et al. [59] used the Agricultural Production Systems sIMulator (APSIM) model to evaluate the effect of different CO_2 scenarios (RCP4.5 and RCP8.5) for corn production in the US and found drought will be the largest factor affecting production. However, they stated that combined impacts of temperature and water stress need to be evaluated in breeding programs and adaptation strategies [59]. Earlier, Jin et al. [60] evaluated the algorithms in 16 different corn models and concluded that heat and drought stress was best simulated when models used event-based heat and water stress descriptions, accounted for nighttime temperature stresses, and evaluated the interactions of multiple stresses. Crop models allow for an assessment of the role of genetics and management on productivity for a range of present and future environmental conditions. Hatfield and Walthall [31] utilized this concept as the G x E x M (genetics × environment × management) framework to determine how these interactions would need to be understood to provide food security for the future population growth.

There have been efforts to combine observations with crop simulation models to evaluate changes in yield and yield stability. Leng [61] found yield variability across the US Corn Belt has decreased from 1980 to 2010 with climatic variability the major factor affected variability among years and regions. He found that statistical models explained more of the yield variation than crop simulation models. Bhattarai et al. [62] used the Environmental Policy Integrated Climate (EPIC) model with the combined results for eight general circulation models to show that under low and medium carbon scenarios, corn yields during the period 2080–2099 increased compared to the 2015–2034 period, while under the high carbon scenario yields during these same periods decreased. Lychuk et al. [63]) also used EPIC for the southeastern United States and found in the near-term corn yields increased, but from 2066 to 2070 yields decreased 5–13% because of the increased temperature stress. Huang et al. [64] combined field experiments with crop simulation models to evaluate the potential effect of different growing season length corn hybrids and found the longer growing season hybrid did not yield as high as the medium length hybrid. These results suggest that efforts be placed in evaluating the

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efficiency of plant growth relative to the changes in temperature and the accumulation of growing degree days.

The Global Agro-ecological zones model (GAEZ) categorizes areas suitable for crop production by climate, soil, terrain, management, and the specific growth limitations of crops, among others [65, 66]. One essential concept of GAEZ climate module is the temperature growing period (LGP_t), where air temperature is used as a proxy to estimate days of the growing period with optimal, sub-optimal, and no suitable crop production conditions for a specific crop. The growing period L is defined as the number of days with average daily temperature > 5°C (i.e., LGP_{t5}). The corn-specific LGP_t's are summarized in **Table 1**. For example, assume a temperate corn cultivar for grain production with a total growing period between 90 and 180 days. During this period average daily air temperature shall not decrease below 5°C, and the number of days with daily average air temperature between 10 and 15°C shall be below ⅕ of the total growing period to reach optimum growing conditions. In addition to air temperature, the length of the growing period is further limited by the moisture regime, defined as actual ET ≤ 0.5 * reference ET.

The GAEZ model also estimates potential yield of a specific crop in a specific agro-ecological zone, and applies constraint factors, such as heat or water stress, to calculate actual yield and yield gap. For example, periods of potential water stress occur when actual ET is below the total water requirement of a crop, maximum ET, and the difference between both cannot be compensated by precipitation, plant available water, or irrigation. Maximum ET is calculated as reference ET multiplied by crop coefficient k_c. Maximum ET is crop specific and changes during crop development by applying crop-development specific k_c values (**Figure 6**). The derived water stress data is then used to calculate yield constraining factors. The GAEZ model

Cultivars	**Tropics lowland**	**Tropics highland**	**Subtropics-temperate**	**Subtropics-temperate**
Crop	Grain	Grain	Grain	Silage
Growing period L (LGP_{t5}) (days)	90–120	120–300	90–180	105–180
Sub-optimum conditions	$LGP_{t<10} = 0$	$LGP_{t>25} = 0$	$LGP_{t<5} = 0$	$LGP_{t>30} = 0$
	$LGP_{t10–15} < 0.167*L$	$LGP_{t<5} = 0$	$LGP_{t10–15} < 0.250*L$	$LGP_{t<5} = 0$
		$LGP_{t10–15} < 0.500*L$		$LGP_{t10–15} < 0.667*L$
		$LGP_{t20–25} < 0.333*L$		$LGP_{t25–30} < 0.500*L$
Optimum conditions	$LGP_{t<15} = 0$	$LGP_{t>25} = 0$	$LGP_{t<5} = 0$	$LGP_{t>30} = 0$
		$LGP_{t<5} = 0$	$LGP_{t10–15} < 0.200*L$	$LGP_{t<5} = 0$
		$LGP_{t10–15} < 0.500*L$		$LGP_{t10–15} < 0.500*L$
		$LGP_{t20–25} < 0.333*L$		$LGP_{t25–30} < 0.333*L$

Adapted and simplified from [66]

Table 1. Corn growing period L (LGP_{t5}), optimum, and sub-optimum conditions of tropical lowland, tropical highland, and subtropical and temperature cultivars for grain production, as well as subtropical and temperate cultivars for silage production.

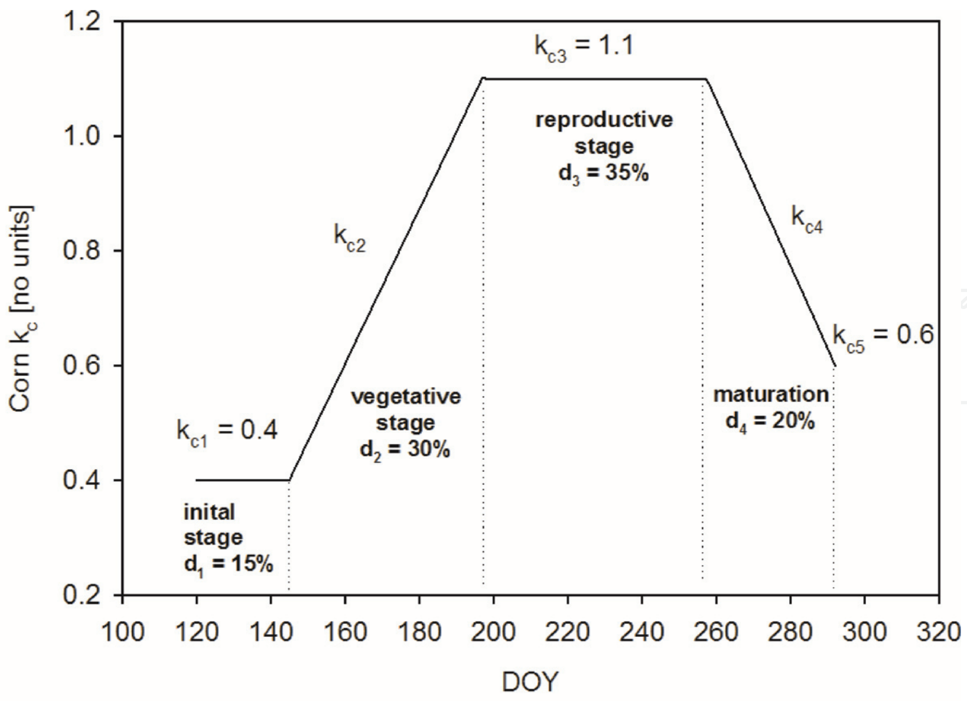

Figure 6. Crop development specific k_c values for corn: k_{c1}, k_{c2}, k_{c3}, and k_{c4} applies for the initial (d_1), vegetative (d_2), reproductive (d_3), and maturation (d_4) development period, respectively. Crop coefficient k_{c5} applies to the end of the growing period. Corn k_{c2} and k_{c4} data are linearly interpolated between k_{c1}, k_{c3}, and k_{c5}. The four corn development stages make up 15, 30, 35, and 20% of the total growing period. Data, equations, and redrawn graph according to IIASA/FAO [66]. In this example, total growing period (day of planting until harvest) was 173 days, for two corn fields nearby Ames, IA, USA from 2006 to 2017.

also determines which production areas are threatened by climatic changes by applying different climatic scenarios. Using this approach, Teixeira et al. [67] estimated that 5 Mha of cropland suitable for corn production are at risk due to climate change induced heat stress, and that yield declines are expected especially in the Northern hemisphere between 40 and 60°N latitudes.

One of the large challenges and opportunities for simulation models will be to incorporate the expected changes in insect and disease populations affecting corn production and link this with the production models. Integration of these two aspects into a single framework will allow for a more complete assessment of the corn production system being experienced by producers.

7. Conclusions

Climate impacts on corn production due to the changing temperature and precipitation regimes in the corn growing areas. The largest impact of these changes will be at the local scale where within season weather induced by the change in climate will become more noticeable. Increasing temperatures will increase the rate of phenological development during the vegetative and reproductive stages; however, the most negative effects will be exposure to high

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temperatures during the pollination and grain-filling stages. The largest impact on corn production will remain linked to the availability of soil water through precipitation and variation in precipitation during the grain-filling period will have the most detrimental impact on corn production. To overcome the effects of climate change there will be shifts in areas where corn is produced; however, these shifts may not be into areas with the capacity of the soil to support high production or have large variation in yield among years due to the variation in within season weather [33]. What will be critical is to increase our understanding of the G × E × M interactions as suggested by Hatfield and Walthall [31] in order to reduce the risk in production from a changing climate. What will be critical will be to use our current knowledge base (i.e. genetic resources (G) and management techniques (M)) to determine the viability of potential adaptation strategies to overcome climate changes (E). Combining experimental studies with crop simulation models will advance our understanding of the complex interactions occurring between the biological system and the physical environment and guide us toward viable adaptation practices with the potential to offset the negative impacts of climate change.

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