2014. Proceedings of the Indiana Academy of Science 123(2):95–102

A CONCEPTUAL MODEL FOR ASSESSMENT OF CLIMATE EXTREMES THAT AFFECT CORN YIELDS

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ABSTRACT. The USA Corn Belt was examined to assess the impacts of observed climate change on corn production for the period 1960–2012. Given a modified definition of a Corn Belt State, 13 states were included in the study. Temperature and precipitation trends during the growing season (April–September) showed the following: a) slight warming of 0.73°F, b) increase in growing season of 9 days, and c) mean precipitation increase of 5.51 cm (2.17 in), which along with technological advancements, support the observed increase of 1.7 bushels per acre per year for the period. A conceptual model assessed the impacts of extreme weather and climate on corn yields in bushels per acre. This model is represented by an Upper Bound (based on technological advancements), and a Lower Bound that is defined as the difference between the mean production and the Upper Bound. All values that fall below the Lower Bound were defined as extremely poor yields that can be attributed to extreme weather and climate events. The model was applied to the entire Corn Belt Region for the period 1960–2012. The years 1983, 1988, 1993, and 2012 were identified as extreme events (which are well-recognized in the agroeconomic community). The benchmark model framework can be extended through the 21st century to monitor the number of extreme events and the magnitude of their departure from the Lower Bound, and it is presented as an instrument for assessing climate change impacts on corn yields.

Keywords: Corn Belt, extreme weather/climate, yields

INTRODUCTION

The "Corn Belt" of the United States of America (Fig. 1) is a region of the world known for food production (see Kucharik & Ramankutty 2005). The soil constituents, combined with a favorable climate, have made this area a highly productive food source region for humankind for over five decades. Increasing corn yields from this area are well-recognized, which can be largely attributed to technological advancements. Genetic improvements and enhanced mechanization in the 1930s started the climb in corn yields that achieved record maxima in 1960 and again in 1982 (Thompson 1986). An important question, that continues to gain attention, focuses on the potential role of climate change on corn yields (including current climate trends as well as the prediction of continued global warming through the 21st century). Kaufmann & Snell (1997) estimate that 19% of the variability in corn yield is due to climate variables, and approximately 74% is explained by technology and related factors (such as fertilizers, pesticides, seed varieties, planting methods, labor, and capital). Lobell & Asner (2003) used county level USDA yield information from 1982 to 1998 to study the impacts of climate change on the overall trends in crop yields. They concluded that previous estimates of increased corn yields attributed to technological advances were overestimated by approximately 20% due to climate-driven increases in yield.

It is further noted that the complexity in explaining the various causes of rising corn yields is somewhat difficult. Sacks & Kucharik (2011) have provided a nice overview of this complexity and the contributions of many factors, such as earlier planting dates due to an increase in the number of Growing Degree Days (GDD) necessary for corn maturation. Additional intricacies include the factors that affect leaf and plant development, as well as the grainfill period. Realizing these and other complexities, this analysis presents a somewhat simple approach to separate direct climate effects (i.e., trends in temperature, length of the growing season, and precipitation in the Corn Belt) from all other factors. Specifically, a conceptual model is developed and implemented with observational data to estimate the

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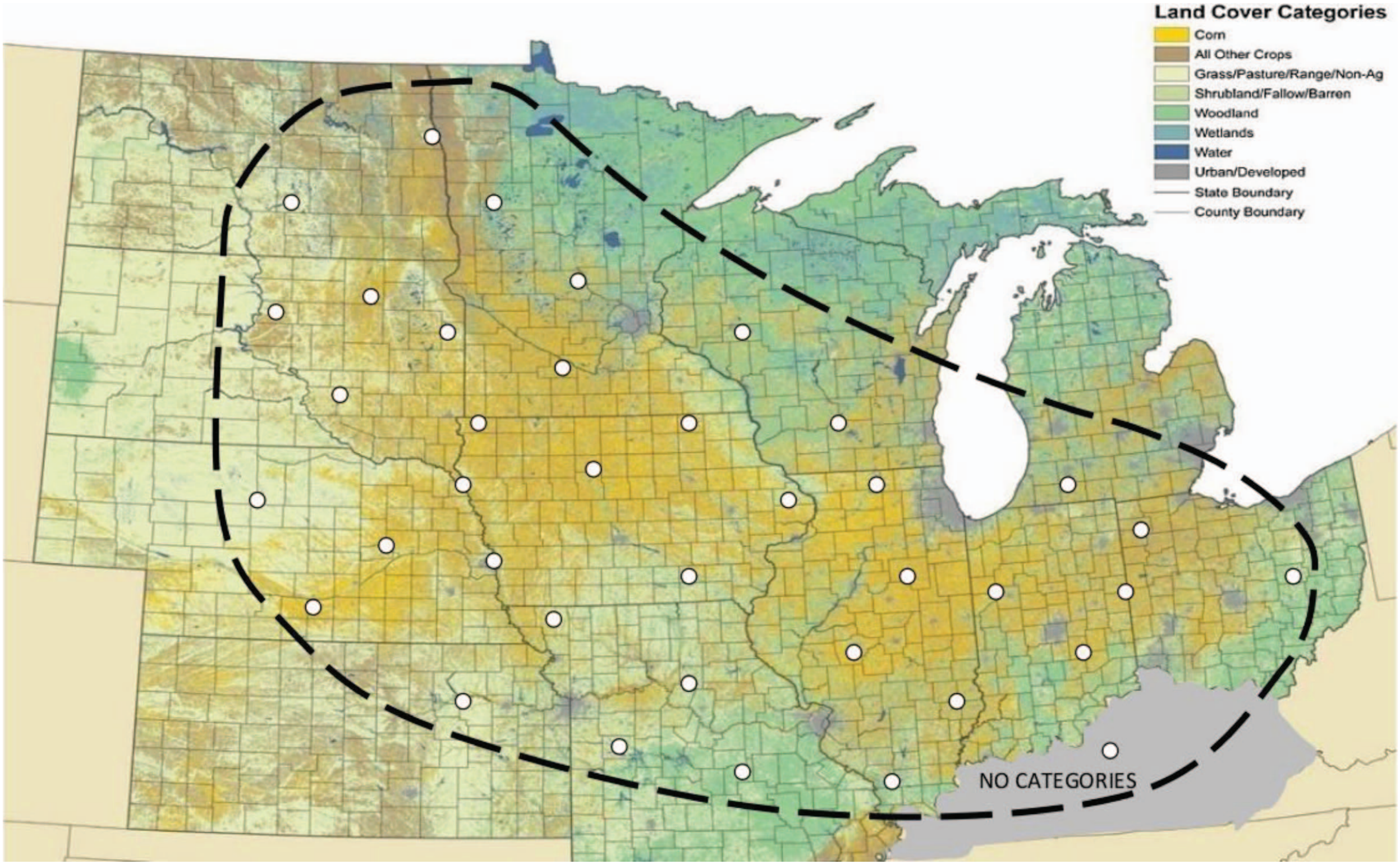

Figure 1.—Land Cover Categories for the Corn Belt region (see http://www.esri.com/mapmuseum/mapbook_gallery/volume24/images/agriculture2_lg.jpg). This study has defined the "Corn Belt Region" to include the states that averaged more than 150,000,000 bushels of corn per year for the 2000–2009 decade. A dashed line has been drawn to show the region, as well as the location of the 38 stations selected for the study.

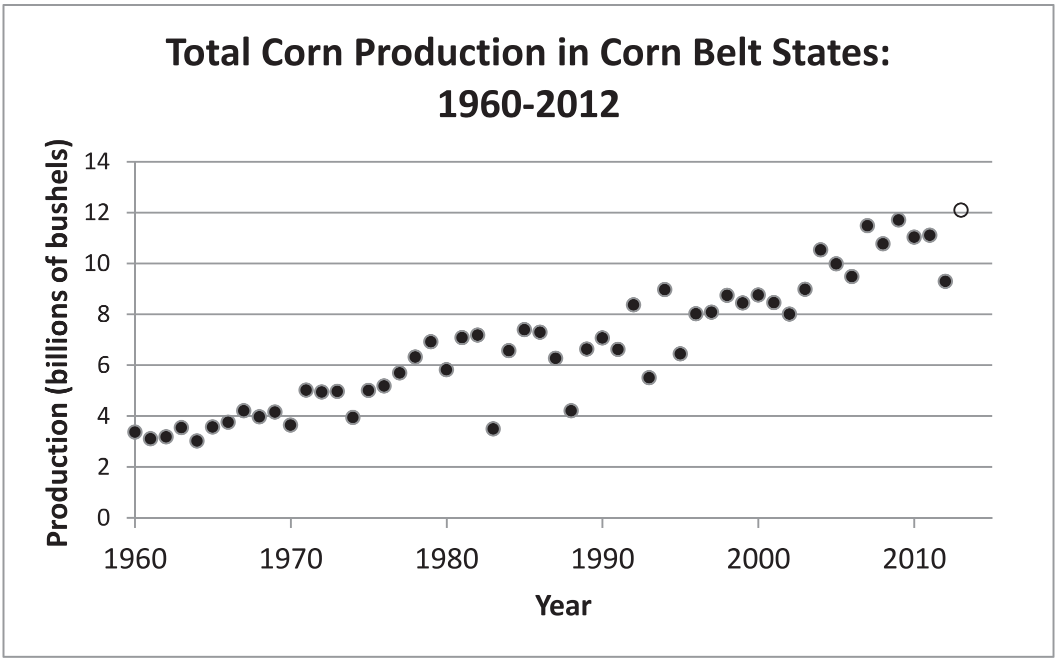

Figure 2.—Total annual corn production (bushels) in the 13-state Corn Belt Region for the period 1960–2012 (NASS 2014). A new record productivity is denoted for 2013 with an open circle.

roles played by technology advancements, mean weather and climate conditions, and extreme weather events, on a climate time scale.

ASSESSMENT OF WEATHER AND CLIMATE EFFECTS

The Corn Belt Region for this study includes any state that exceeded an average annual yield of 150 million bushels for the decade 2000–2009. This resulted in the inclusion of 13 states, including North Dakota, which has not frequently been included in past studies (e.g., Kucharik 2006). Figure 1 shows the vegetative cover for the Corn Belt (identified by the dashed line), as well as the location of 38 stations selected for compiling the climatic data set. These stations have a mean minimum spacing of 145 km, with an average departure from this mean of 20 km. Efforts were made to avoid the clustering of data points, as well as to maintain equal spacing. Annual corn yield data were taken from the USDA's National Agricultural Statistics Service to assess trends through time (NASS 2014). Figure 2 is presented to show the total annual production in the 13-state Corn Belt Region for the period 1960–2012. Recently released 2013 corn data reveal a new record productivity, which is depicted in Fig. 2 as an open circle. Annual productivity has increased from around 3×10^9 bushels in the 1960s to a current production of around 11×10^9 bushels. Realizing the intricacies of farming practices, as well as acres planted for different crops and other considerations, it was decided to examine trend lines and weather/climate effects based on bushels per acre of corn production. Accordingly, Fig. 3 is presented along with a least squares linear fit that shows an r value of 0.934, with an average annual increase of 1.7 bushels/acre. Again, the recent 2013 yield data are included as an open circle. Noteworthy is a record departure below the trend line of 37 bushels per acre for the 2012 growing season, eclipsing previous record departure years of 1988 (26 bushels/acre), 1993 (23 bushels/acre), and 1983 (23 bushels/acre). However, the drought year of 1988 remains the greatest percent departure from the trend.

Spatial and Temporal Variability.—To assess trends and variability in temperature and precipitation throughout the Corn Belt, data from the 38 stations for the six months (April–September) most essential to corn production were collected from the National Climatic Data

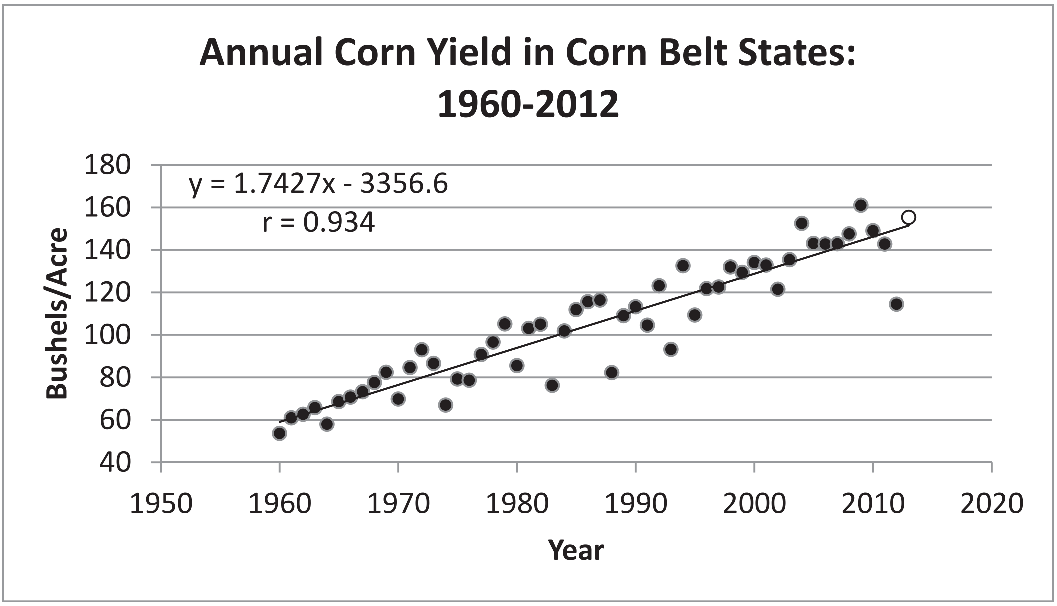

Figure 3.—Variation in corn yields (bushels/acre) for the 13 Corn Belt states from 1960–2012 (NASS 2014). The trend line shows an average annual increase of 1.7 bushels/acre. Recently-released yield data for the 2013 is depicted with an open circle.

Center (NCDC) and analyzed. Further, changes in the length of the growing season, defined as the number of days between the last spring freeze (32°F) and first fall freeze, were computed. These analyses allowed for the opportunity to address the potential role of climate on corn production.

Temperature and length of growing season: The trend in mean air temperature, considering all Corn Belt stations for the period April–September since 1960 (Fig. 4) revealed considerable variability, ranging from 62.4°F in 1992 to 67.4°F in 2012 (with a 0.73°F increase in the mean). In addition to this variability, and even more interesting, is the variability in mean temperature among the 38 selected stations in the Corn Belt (which ranges from +3.7°F in northern Minnesota to −1.7°F in eastern Iowa). The complexity of such spatial variability has also been noted in the study by Kucharik & Serbin (2008), and further treatment of this topic is suggested. The change in the length of the Corn Belt growing season, as defined above, is approximately 9 days, with over 8 of these days gained as a result of the last spring freeze occurring earlier. This increase is comparable to the trend toward earlier start dates for planting of 10 to 12 days (Kucharik 2006; Sacks & Kucharik 2011). Thus, it is reasonable to conclude that some fraction of the increased growing season length can be attributed to a longer freeze-free growing season. When growing season lengths for the 38 stations throughout the Corn Belt Region are examined, large spatial variability is present as expected, ranging from 198 days in southern Missouri to 122 days in northern Minnesota.

Precipitation: Generally speaking, cooler and wetter summers in the Corn Belt favor increased yields, while hot and dry summers are detrimental to production, as seen in the 2012 disastrous crop season (Thompson 1986; Neild & Newman 1990). Although the Corn Belt shows a rather modest growing season mean temperature increase of 0.73°F from 1960 to 2012 (for the fitted line in Fig. 4), a greater percent increase is noted when precipitation trends are considered. Figure 5 shows an increase in mean precipitation for April–September of 5.51 cm (2.17 in) for the period, but again large variability and weak correlation in the trend line are evident.

EXTREME WEATHER AND CLIMATE EFFECTS ON CORN YIELDS: A CONCEPTUAL MODEL

In view of the above discussion on temperature and precipitation variability, it might

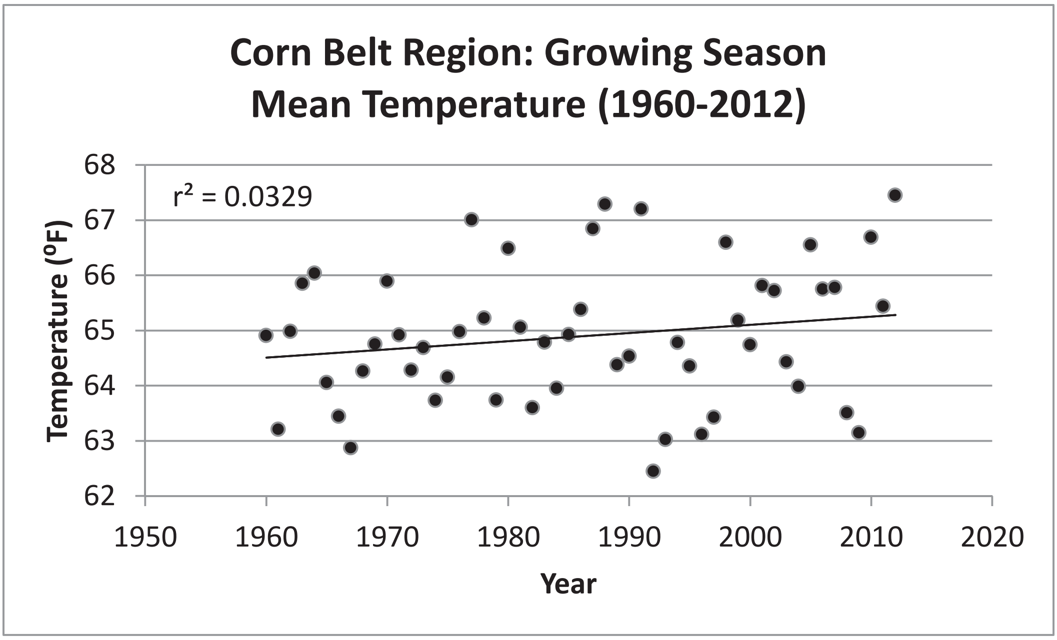

Figure 4.—Variation in the growing season mean temperature (1960–2012) for the Corn Belt Region (NCDC 2014). The slope of the linear fit shows a warming trend of 0.73°F, with evidence of increasing variability through the period.

seem impossible to document the effects of extreme weather and climate on corn yields. However, a unique approach was taken to diagnostically assess the complexities of technology and weather extremes on the climate time scale that affect corn yields. The conceptual model is presented in Fig. 6, which defines an Upper Bound for production that is based on the cumulative effects of technology (which is illustrated in the next section with the 1960–2012 data set). Next, the annual mean for the yield record was plotted, and the difference between the mean line and the Upper Bound defined the equivalent range of corn yield for the Lower Bound. Both the upper and lower bounds are equidistant from and parallel to the mean trend line, and the 53-year data set established these fixed boundaries. Data points in the record that fall below the Lower Bound were defined as low yields attributable to extreme weather and climate events. Increasing severity of extreme weather and climate events results in greater yield departures from the trend line, as noted by the lower dashed line tracing the most extreme low yield values, which fans out through time (Fig. 6). The frequency of seasonal yields that fall below the Lower Bound may also increase with more extreme weather and climate events, a hypothesis worth monitoring in future years. It is again emphasized that the model, and its application, is an instrument for diagnostic assessment of climate change impacts.

Application of the Model.—To show the usefulness of the conceptual model, it has been applied to the entire Corn Belt Region (Fig. 7). Four years of poor yield (1983, 1988, 1993, and 2012) fall below the Lower Bound and are thus classified as occurring under extreme weather and climate events that negatively impacted yields. Not surprising, and as well-known, the two worst years for corn productivity (2012 and 1988) were both characterized by extremely hot and dry conditions during the spring and summer months (Namias 1991; NCDC 2015). The other two years of poor corn productivity displayed other noted scenarios, namely extremely cool and wet conditions throughout the 1993 growing season (Kunkel et al. 1994) and cool, wet conditions early in the growing season followed by hot and dry conditions late in the 1983 growing season.

The Upper Bound, as defined in this study, illustrates the limitations of *extraordinary*

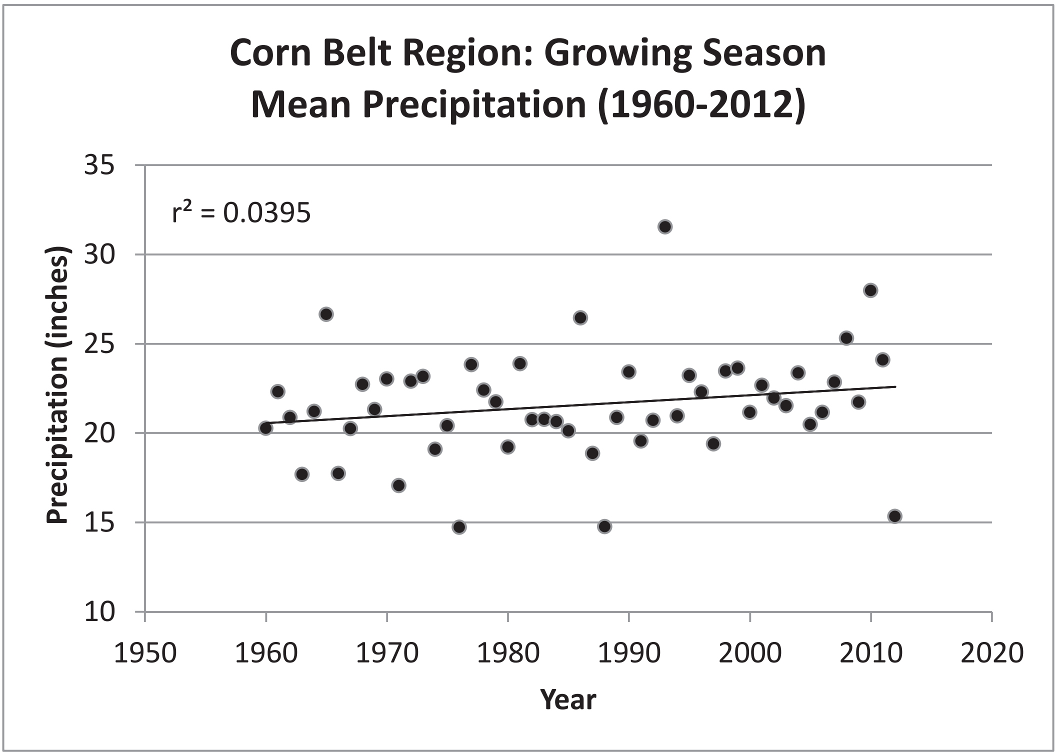

Figure 5.—Variation in the growing season mean precipitation (1960–2012) for the Corn Belt Region (NCDC 2014). The slope of the linear fit shows an increase of 5.51 cm (2.17 in), with evidence of considerable variability through the period.

technological advancements. Five years covering a large span of time (1972, 1979, 1994, 2004, and 2009) had yields near or on the Upper Bound, showing that increases in technology have not been so revolutionary as to reveal a consistent increase in the number of years abutting the Upper Bound, at least since 1960. The four years below the Lower Bound are successfully captured by the methodology of the conceptual model. Finally, the domain of extreme events, highlighted by the crippling 2012 season (Fig. 7), fans out below the Lower Bound, another feature illustrated in the model. As such, the diagnostic methodology in this model is prepared to document the cumulative effects of 21st century extreme weather and climate on corn yields in the USA Corn Belt Region.

DISCUSSION AND CONCLUSIONS

Data for total corn yields, as well as yields of bushels per acre, for the USA Corn Belt region were assessed for the period 1960–2012, along with relevant weather and climate data records. A definition for a “Corn Belt State” was introduced, which qualifies 13 states for analysis. Weather records from 38 selected stations across the Corn Belt were used, which have a mean station spacing of 145 km, with an average departure from the mean of 20 km. The observational data showed that the essential period during which corn is grown in the Corn Belt (April–September) has become wetter and slightly warmer through time, although considerable spatial and temporal variability was noted and can be expected (as seen in the cause of the disastrous 2012 crop season). More research into spatial and temporal variability is warranted, especially with the anticipated continuation of global warming and the associated extreme weather events. The precipitation increase for April–September found in this study is also consistent with the expected increase in conditions that support summertime convective precipitation (namely humidity and CAPE (convective available potential energy), as seen in the study by Trapp et al. 2007).

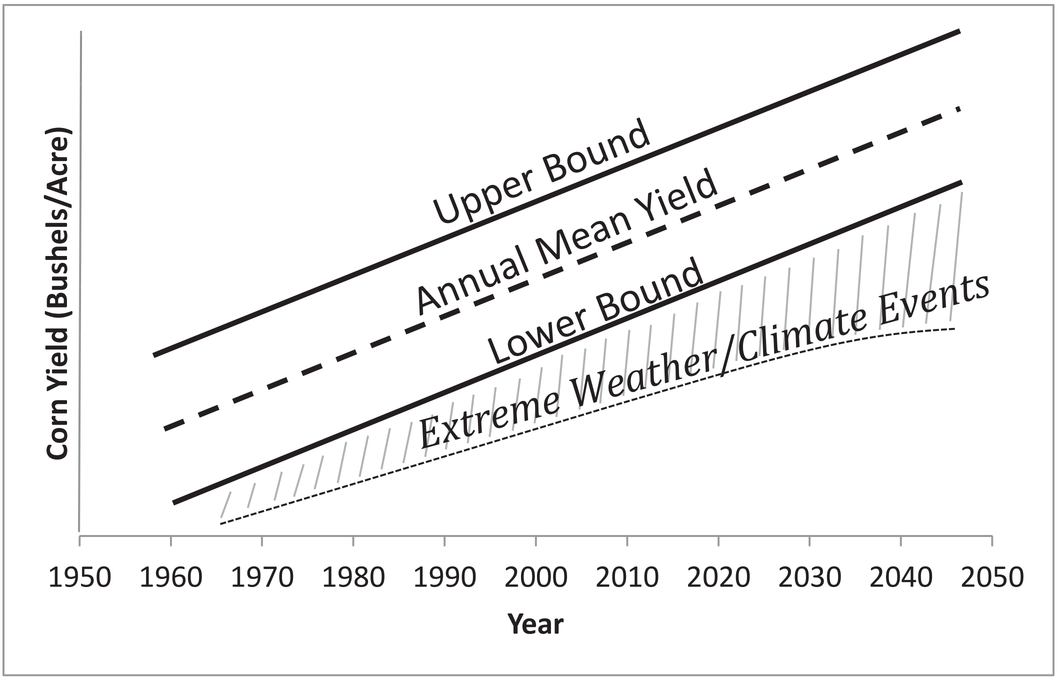

Figure 6.—Conceptual model representing the increase in corn yield with time. Technological improvements define the Upper Bound which, along with climate and weather events, provide a mean annual trend line. The Lower Bound is defined as being equally distant from the mean as the Upper Bound. Annual yields that fall below the Lower Bound are defined as those attributed to extreme weather and climate events.

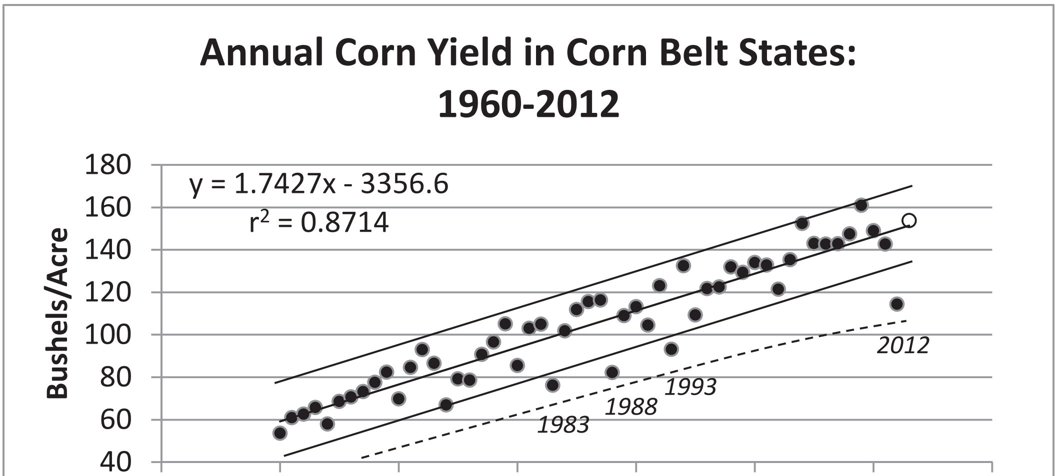

Figure 7.—Annual corn yield for the Corn Belt states during the period 1960–2012. The conceptual model defines four years (1983, 1988, 1993, and 2012) of low yields, attributable to extreme weather and climate events. All features of the conceptual model are illustrated by its application to the 53-year data set.

Based upon the conceptual model, 53 years of data were assessed for the occurrence and effect of extreme weather and climate events on corn yields. This model worked as envisioned, even in the presence of continued increase in annual yields (1.7 bushels per acre per year) contributed in part by technological advancements. Application of the model identified four events that represent extreme weather detrimental to corn yields. These are (from the most extreme to the least extreme in terms of departure from the trend line) 2012, 1988, 1993, and 1983 for the entire Corn Belt Region.

Further, it is important to realize that the model framework presented in this study can be 2012, 1988, 1993, and 1983 for the entire Corn Belt Region. extended through the 21st century (assessing any global warming effect) to monitor and quantify the number of extreme events. Specifically, if there are more extreme weather and climate events (e.g., heat, drought, excessive rainfall), the number of events that fall below the Lower Bound for corn yields may increase, and there also exists the opportunity for more record departures from the mean trend line (as seen in 2012). Thus, this model provides a diagnostic assessment of corn yields, categorizing them based on both technological advancements and climate change.

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Manuscript received 14 August 2014, revised 22 May 2015.