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Assessing the Impact of Year 2012 Drought on Corn Yield in the US Corn Belt Using Precipitation Data

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Abstract: Extreme weather and climate events are likely to cause disastrous consequences for agriculture and food security. This study investigated the impacts of drought in year 2012 on corn yield in the United States Corn Belt by integrating county-level crop yield data from the USDA NASS Quick Stats database and precipitation data from the NCDC GHCN-Daily database. It is found that precipitation over an 8-week period in corn growth stages is critical for corn yield, the logarithm of precipitation during the period explained 55% of corn yield variation. The results indicated the importance of water supply in corn silking stage, and provided an approach to assess the impacts of drought on corn yield quantitatively.

Key words: Corn, drought, yield, precipitation, Corn Belt.

1. Introduction

Climate change involves complex interactions and changing likelihoods of diverse impacts. As rapid population growth and climate change present far-reaching threats to food security, it has become vital to assess the impact of extreme weather events on agricultural productivity. Climate models predicted drastic changes in water availability and increase of land areas in drought in near future due to climate change [1]. Although localized effects may be difficult to predict, the overall severity and extent of drought is projected to increase. These extreme weather events are likely to cause major crop losses, which will have drastic political, economic, and humanitarian consequences [2, 3]. Assessing and responding to these crises require a deep and quantitative understanding of how drought impacts agricultural yield [4].

Currently, corn is the major food crop in much of sub-Saharan Africa, Southeast Asia, and Latin America, while in the United States it is the major cash crop for the Midwestern Corn Belt and is essential to the production of fuel and livestock [5]. While plant breeding and genetic engineering have been used to improve the drought-tolerance of corn, drought during critical development periods still has serious consequences [6]. This vulnerability was demonstrated as recently as 2012, when severe summer drought over much of the United States Midwest crippled corn yields and drove prices to record highs [7]. Many studies have been conducted to quantify the effect of drought on corn yields. By controlling watering regimes to simulate drought and comparing the characteristics of different corn hybrids, experiments have profiled the effect of water stress throughout corn growth and development. These studies indicate that adequate moisture is crucial during the silking stage, when water stress can delay development of silks (which receive pollen for fertilization) and prevent kernel formation [8-10]. Water stress after this stage, when plants direct resources towards kernel development, can also severely reduce yield [8, 9].

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Estimating corn yields using agricultural data also offers important insights. Existing methods include sophisticated models which account for factors including plant physiology, soil characteristics, and even economic factors [2, 11]. While these approaches give excellent results for small regions where parameters such as soil type, variety, or planting date are known, the large number of parameters limits their applicability when detailed data are not available. Other approaches have used climate data and historical yield to fit a model, but this has generally been limited to individual pilot fields, a few counties, or state-level average data [12-14].

This study addressed these issues by integrating historical precipitation data from the National Climatic Data Center's GHCN (Global Historical Climatology Network) -Daily database [15] and yield data from the NASS (National Agricultural Statistics Service) [16] at the county level in order to assess and quantify the impact of precipitation on corn yield over a large area of the United States Corn Belt.

2. Data and Method

2.1 Study Area

In the United States, corn is the major cash crop for the Corn Belt and is essential to the production of fuel and livestock. The Corn Belt includes Iowa, Illinois, Indiana, and parts of Michigan, Ohio, Nebraska, Minnesota and Missouri. In this study, five major corn-producing states in the US Corn Belt were chosen: Iowa, Illinois, Indiana, Ohio, and Minnesota, containing a total of 434 counties. Year 2012 was a major drought year across the Corn Belt during the period of maximum water use for corn. As illustrated in Fig. 1, in the mid-July of year 2012, during the corn silking stage, most of the Corn Belt suffered from moderate to extreme drought except the eastern part of Minnesota. Especially, severe and extreme drought affected Illinois, Indiana, and eastern region of Iowa. Nebraska is also a major corn producer, but much of its corn crop is usually irrigated using readily available water from the Ogallala Aquifer [17]. According to the USDA NASS data, the total corn planted area of Nebraska in year 2012 is 10,000,000 acres, among which 5,850,000 acres were irrigated [16]. Thus, data from Nebraska were excluded in this study to reduce confounding factor of irrigation. The five selected states have low irrigation rates, and thus it is appropriate to compare corn responses to drought with precipitation data.

2.2 Study Period

Corn is a crop with high water requirements. Moisture stress at any of the corn growth stages, especially the silking period, can cause potential yield reduction. Figs. 2 and 3 show how the growth of corn progresses on weekly basis using percentage emergence and silking rates (data were obtained from NASS Quick Stats 2.0 database [16]). In mid-May of 2012, most corns in the study area emerged in vegetative growth stages (Fig. 2). The silking stage varied from early June to mid-July (Fig. 3). Previous studies have demonstrated that water stress during the silking impedes fertilization and greatly reduces corn yields [8-10]. Thus this present study focused on the phonological stages of corn growth from May to July of year 2012.

2.3 Data

The GHCN-Daily contains daily climate records from over 75,000 stations around the world. Maximum and minimum air temperature, snowfall, snow depth, and daily precipitation are the primary variables

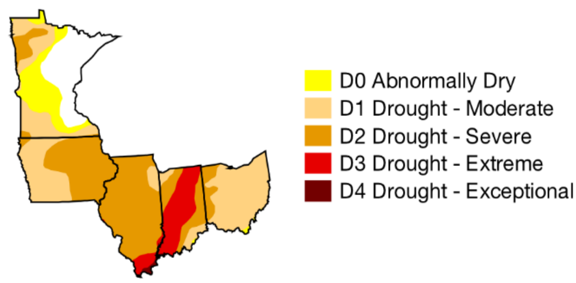

Fig. 1 Drought conditions over the study area in mid-July, 2012. Data were obtained from the U.S. Drought Monitor (http://droughtmonitor.unl.edu).

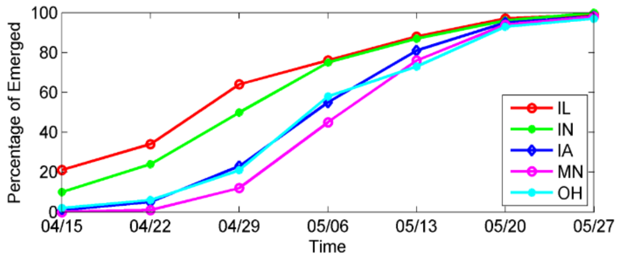

Fig. 2 Weekly corn progress in year 2012 measured in percentage emerged.

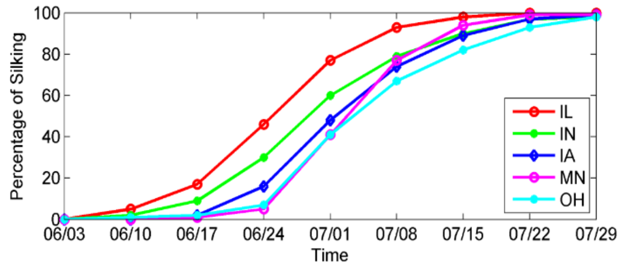

Fig. 3 Weekly corn progress in year 2012 measured in percentage silking.

provided by these stations [15]. GHCN contains the most complete collection of United States daily climate summaries. Precipitation data were obtained from the GHCN-Daily database, in the form of daily precipitation records. Using the latitude and longitude provided for each station, the stations were grouped by county and daily mean precipitation was calculated on a per-county basis.

USDA's NASS provides comprehensive data sets and statistics of crop planting area, yield, production, etc., at county and state levels. In this study, county-level corn planted area, and yield data, and state-level corn growth progress data for the study area were obtained from the NASS Quick Stats 2.0 database [16], using records from annual NASS surveys.

2.4 Method

Corn yields varied locally throughout the study region, likely due to factors such as cultivation practice (planting conditions, fertilizer usage, etc.) and local geographic variation (soil type, climate, etc.). In order to reduce the confounding effect of these variables, the yield anomaly was used as the response variable. The expected yield was calculated by fitting a least-square linear regression line to yield time series data from 1960 to the year preceding the target year (or 1960-2011). For this time period, increases in yield seemed to follow a linear pattern, justifying the use of this method to calculate expected yield. The yield anomaly was calculated as the percentage difference between the projected and observed values.

Total precipitation was calculated for each 8-week interval within corn growth stages in the study year. When measurements were missing, the mean of available precipitation data multiplied by the period length was used if more than half of the values were available; otherwise the county was excluded.

Examination of the data revealed that the relationship between precipitation and yield was non-linear. However, transforming precipitation by taking its base-10 logarithm produced linear relationship between the predictor and response variables, with no clear pattern in the residuals and relatively constant variance around the trend line. Thus, the logarithm of precipitation data was used for analysis in this study.

3. Results and Analysis

Correlation coefficients between $\log_{10}$-transformed total precipitation and yield anomaly were calculated for each 8-week period, as shown in Fig. 4, where x-axis represents center of the 8-week interval, and y-axis indicates correlation coefficients. For 8-week periods centered from early to late June, the correlation coefficients are higher than 0.7. These periods are corresponding to later corn vegetative stages and whole silking stage, in which water supply is critical for corn yield.

The maximum correlation was found for the 8 week period from May 6th to June 30th. In order to quantify the effects of drought, the yield anomaly was plotted against the transformed precipitation for the period of maximum correlation, i.e., the critical period requiring water for corn growth. Least-square linear regression

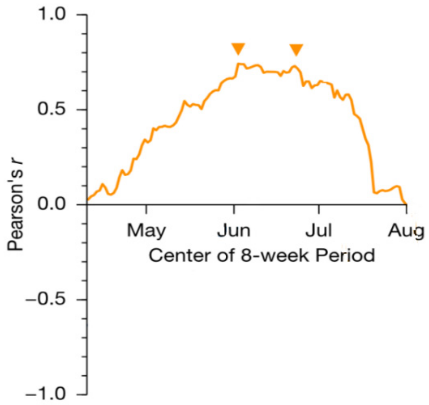

Fig. 4 Pearson product-moment correlation coefficient between log_{10}-transformed 8-week precipitation totals and yield anomaly for different periods 2012. Peak values are indicated with colored triangles.

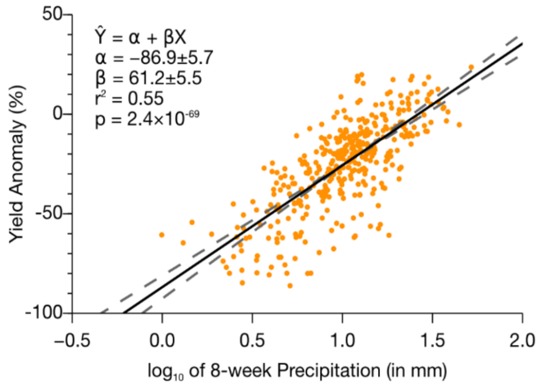

Fig. 5 Least-squares regression for yield anomaly using transformed precipitation (in the period of maximum correlation). The 95% confidence interval for the regression line is shown with dashed lines.

with the transformed precipitation as the predictor variable was used to estimate the impact of low precipitation on yield (Fig. 5). The coefficient of determination (r^2) is 0.55 with p values near 0. So variation in the log_{10}-transformed precipitation during critical period explained 55% variation in corn yield anomaly. The result implies a linear decrease in yield associated with each ten-fold decrease in precipitation over the critical period. Thus, low precipitation during corn growth stages in year 2012 contributed to most reduction of corn yield in the U.S. Corn Belt.

4. Conclusion and Discussion

In this study, precipitation data over corn growth period from later vegetative stage to silking stage were analyzed to assess the impact of drought on corn yield during year 2012 in the U.S. Corn Belt. It is found that precipitation over the period near silking stage of corn development explained 55% variation in corn yield anomaly so water supply near silking stage is critical for corn yield. The strong correlation between precipitation and corn yield anomaly suggests the critical impacts of drought on corn yield in year 2012.

The proposed approach in this paper discovered the quantitative linkage between drought and corn yield, which is critical for accurate assessment of climate impacts on food security. However, precipitation during the identified critical period only explained 55% variation in corn yield anomaly, other factors, such as temperature and length of growing season may also contribute to the variation of corn yield anomaly. Further study to include more factors will be conducted in near future to characterize the impacts of drought in more details.

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