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Trends and Variability in U.S. Corn Yields Over the Twentieth Century

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ABSTRACT: The United States is currently responsible for 40%–45% of the world's corn supply and 70% of total global exports [the U.S. Department of Agriculture–National Agricultural Statistics Service (USDA–NASS)]. Therefore, analyses of the spatial and temporal patterns of historical U.S. corn yields might provide insight into future crop-production potential and food security. In this study, county-level maize yield data from 1910 to 2001 were used to characterize the spatial heterogeneity of yield growth rates and interannual yield variability across the U.S. Corn Belt.

Widespread decadal-scale changes in corn yield variability and yield growth rates have occurred since the 1930s across the Corn Belt, but the response has varied substantially with geographic location. Northern portions of the Great Plains have experienced consistently high interannual corn yield variability, averaging 30%–40% relative to the mean. Increasing usage of irrigation in Nebraska, Kansas, and Texas, since the 1950s, has helped boost yields by 75%–90% over rain-fed corn, creating a yield gap of 2–4 T ha^{-1} between irrigated and nonirrigated corn that could potentially be exploited in other regions. Furthermore, irrigation has reduced interannual variability by a factor of 3 in these same regions. A small region from eastern Iowa into northern

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Illinois and southern Wisconsin has experienced minimal interannual yield variability, averaging only 6%–10% relative to mean yields.

This paper shows that the choice of time period used for statistical analysis impacted conclusions drawn about twentieth-century trends in corn yield variability. Widespread increases in yield variability were apparent from 1950 onward, but were not significant over the entire 1930–2001 period. There is also evidence that yield variability decreased from the early 1990s to 2001. Corn yield growth rates peaked at an annual-average rate of 3%–5% in the 1960s (124.5 kg ha^{-1} yr^{-1}), but have steadily declined to a relative rate of 0.78% yr^{-1} (49.2 kg ha^{-1} yr^{-1}) during the 1990s. A general inverse relationship between increasing corn yield and decreasing yield growth rates was noted after county-level yields reached 4 T ha^{-1}, suggesting that widespread, significant increases in corn yield are not likely to take place in the future, particularly on irrigated land, without a second agricultural revolution.

KEYWORDS: Agriculture, Climate, Variability

1. Introduction

Human population continues to rise around the world. The United Nations (United Nations 2003) estimates that there could be between 7.4 to 10.6 billion people on this planet by the year 2050. It has been estimated that pressure from rising global population will cause the demand for cereals and grains to escalate another 40% by 2020 (Duvick and Cassman 1999), or an annual-average increase of 1.3%. Cassman (Cassman 1999) suggests that annual-average corn yields must reach 70%–80% of their potential ceiling (~24 T ha^{-1}) within the next 30 yr to keep pace with the growing global population. Furthermore, per capita food consumption rates are also steadily increasing around the world, particularly in developing nations with increasing incomes. When both population and food consumption rate increases are accounted for, it is estimated that food production will need to triple by the year 2050 (Kendall and Pimentel 1994).

Increases in global food production can be achieved either by expanding the global cropland base or by increasing the current productivity of existing agricultural landscapes. The potential for expanding our cropland base has been exhausted because no fertile frontier remains, and the remaining potentially cultivable lands are found in tropical South America and Africa. The clearing of these landscapes for cultivation will mean the loss of enormously valuable resources of tropical rainforests and potential feedbacks to the global climate system (Carvalho et al. 2001; Costa and Foley 2000; Henderson-Sellers et al. 1993). Thus, it appears that the only realistic means to increase global food production is through increasing crop yields.

During the twentieth century, increases in food production have more than kept pace with population growth. Corresponding increases in cropland yields have been attributed to Green Revolution technologies, including the use of new high yielding varieties of rice, maize, and wheat, and through the application of fertilizers, irrigation, and pesticides. However, the question remains as to whether future crop production increases can keep pace with population growth. Furthermore, the future interannual variability of crop production is also uncertain due to the uncertainty of future climate and extreme weather events, but is equally important to global food supplies, the global economy, farmer profitability, and future land-use decision making.

Because the United States is responsible for 40%–45% of the world's corn supply and 70% of total global exports [the (U.S. Department of Agriculture–National Agricultural Statistics Service) USDA–NASS 2003], analyses of the spatial and temporal patterns of historical U.S. crop yields might provide much needed insight into future crop production potential and food security. The United States has some of the most intensively managed agricultural systems in the world and has some of the highest yields [production per unit of land area; (the Food and Agriculture Organization) FAOSTAT 2002]. While the annual-average U.S. corn yield has steadily increased since the 1950s and has reached a current average value of approximately 8.5 T ha^{-1} in 2002 [136 bushels per acre (bu ac^{-1}) Figure 1], the relative (percentage) gain over each previous year has steadily declined since the 1960s to less than 1.5% growth per year in 2001, after peaking in the early 1960s at 3%–5% (Mann 1999; Figure 2). Recent studies have clearly shown that this disturbing trend of diminishing growth (annual increases in productivity) of crop yields at the national level in the United States have plummeted to an annual growth rate that will be unable to keep pace with exponential population growth (Duvick and Cassman 1999).

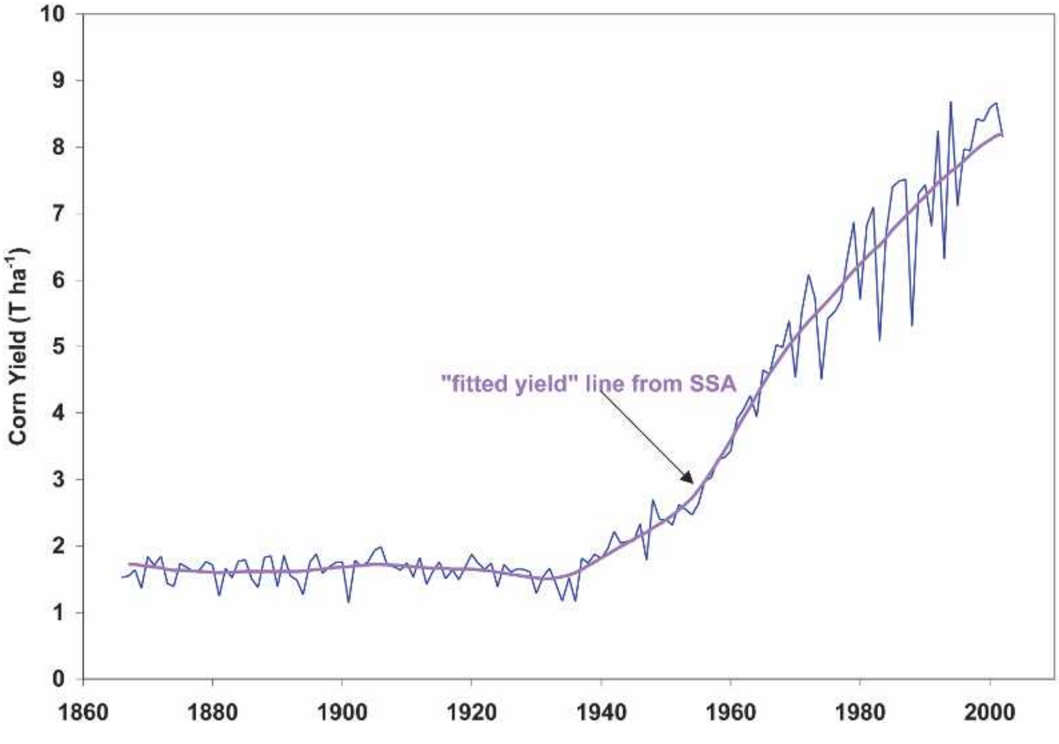

Figure 1. The U.S. national corn yield average data from the USDA (blue line) and "fitted yield" line (pink line) using SSA.

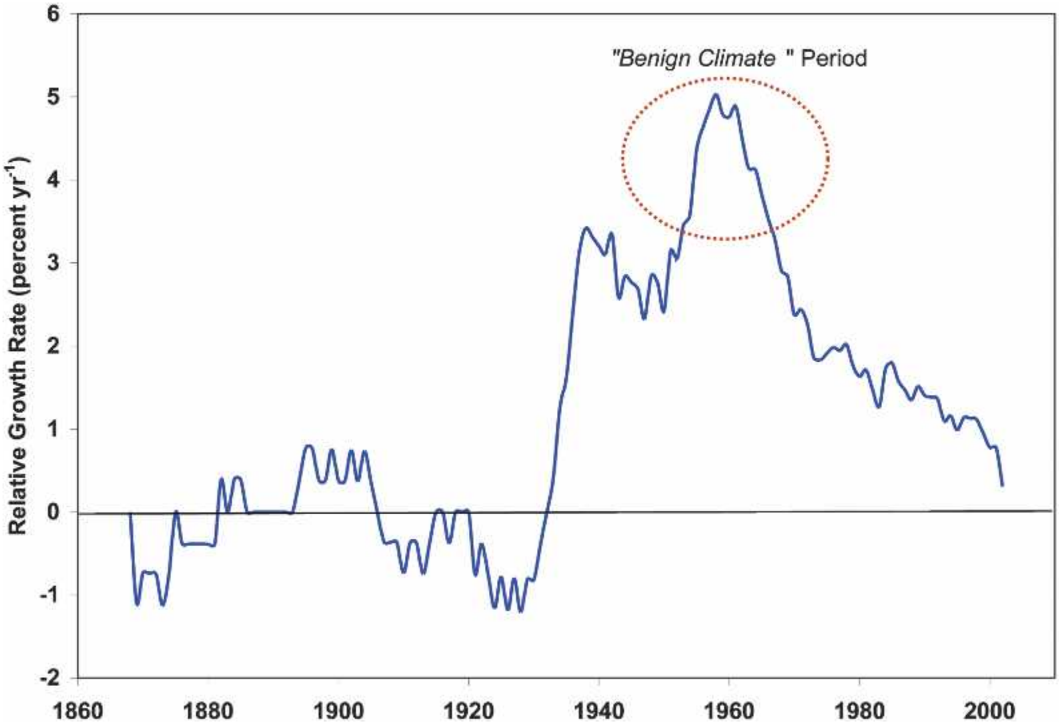

Figure 2. Annual corn yield growth rate (% yr^{-1}) calculated from the fitted yield line in Figure 1.

Besides the growing body of evidence that suggests significantly reduced yield gains in the near future, there are indications that U.S. corn yield variability has escalated since 1950 in the United States (Naylor et al. 1997; Reilly et al. 2003). These conclusions suggest that as farmers near potential corn yield ceilings across the U.S. Corn Belt, they are potentially at a higher risk for catastrophic losses. Naylor et al. (Naylor et al. 1997) point out that as yield ceilings are approached, poor weather years can result in more significant deviations (negative) from perceived average yields (i.e., statistically fitted yield line) than favorable weather years do, primarily because yields have further to fall from the perceived average. Additionally, as yield growth rates plateau, interannual variability due to year-to-year weather fluctuations are easier to detect and separate from the overall trend. Therefore, this may leave the false perception that the frequency of extreme weather occurrences (e.g., drought, early frost, spring flooding) that are detrimental to crop production may also be increasing.

1.1. Previous spatial analyses of crop yield data

Considerable speculation about future trends and patterns of crop yield has been accomplished by earlier studies using statistical analyses of historical interannual volatility and growth rate trends. In the past two decades, several investigations have documented historic changes of maize and soybean yield across the United

States using state- or national-level yield data (Garcia et al. 1987; Baker et al. 1993; Naylor et al. 1997; Reilly et al. 2003), individual on-farm yield results from experimental trials or yield "contests" (Duvick and Cassman 1999), and simulation modeling (Andresen et al. 2001). These studies have attributed the increasing corn yield and changes in yield stability (Thompson 1986; Thompson 1988; Naylor et al. 1997) to technological advancement (e.g., plant genetics and improved machinery), the increased reliance on irrigation and agrochemicals to enhance soil nutrient status and resistance to pests, a prolonged photosynthetic period (Tollenaar and Wu 1999), regional climate change and variability (Lobell and Asner 2003), and a combination of all the aforementioned factors.

In a recent analysis, Lobell and Asner (Lobell and Asner 2003) used county-level USDA yield information from 1982 to 1998 to study the impact of climate change on the overall trends in corn and soybean yield. They determined that previous estimates of increases in corn yield attributed to technological advances might have been overestimated by approximately 20% because of accompanying climate-driven increases in yield. An earlier study by Kaufmann and Snell (Kaufmann and Snell 1997), who analyzed county-level data from the eight largest corn-producing states from 1969 to 1987, estimated that roughly 19% of the variability in corn yield observed was due to climate variables, and about 74% of the variability can be explained by social variables (e.g., capital, labor, fertilizers, pesticides, etc.).

To our knowledge, the most comprehensive spatial studies of crop yield variability have been performed by Huff and Neill (Huff and Neill 1982) and Carlson et al. (Carlson et al. 1996). Huff and Neill (Huff and Neill 1982) analyzed the temporal and spatial relationships between corn yield and weather (e.g., July precipitation) over five Midwestern states using USDA-reported crop district data. Their results illustrated definitive correlations between July rainfall variability (coefficient of variation) and corn yield during 1931–75. Carlson et al. (Carlson et al. 1996) investigated Midwestern corn yield variability in relation to extremes in the Southern Oscillation.

1.2. Shortcomings of previous work

While significant progress has been made in the study of corn yield trends and variability and their response to past management or climate and weather patterns (Carlson et al. 1996; Mauget and Upchurch 1999; Legler et al. 1999; Lobell and Asner 2003; Reilly et al. 2003) at national, state, and individual field scales, it is desirable to quantify a more complete time–space correlation between yield variability, growth rate trends, and climate. Unfortunately, because the majority of previous published studies have used national, crop-reporting, district- or site-specific data in the United States, we have a limited understanding of how declining growth rates in corn yield or changes in interannual variability vary across the U.S. Corn Belt in a time *versus* space context.

Producers and those involved in future policy decision making would benefit from a comprehensive analysis of 1) which regions have shown significant trends in increasing or decreasing variability during the twentieth century, 2) which regions demonstrate the lowest and highest interannual variability and the greatest likelihood of future growth of corn yields during the next several decades, and 3) how irrigation has impacted corn yield and production volatility. These analyses could aid in developing a better understanding of what the potential is for future increases in crop production, and eventually, how crop yield and climate variability are related.

To our knowledge, few studies have used the county-level USDA–NASS yield data to characterize patterns of annual maize yield growth rates or interannual variability across the U.S. Corn Belt. The scale of these data is particularly relevant and useful because 1) counties represent the smallest subunit at which state-level crop yield information is partitioned and reported, based on destructive sampling (Prince et al. 2001; 2) it represents an aggregation and average result of varied farm practices used in a region that is typically experiencing similar climate regimes; and 3) further research could use these data to investigate the correlations between long-term gridded climate data and county-level yield (e.g., Lobell and Asner 2003).

1.3. Objectives

The primary objectives of this work were to provide insight into the following questions.

1) How does the length of the corn yield record used in analysis impact conclusions drawn about the trends of interannual corn yield variability during the twentieth century?
2) What are the spatial patterns of positive and negative deviations of yield from the long-term mean trend?
3) Which regions have consistently shown the highest variability and risk for significant departures (>20%) from expected long-term means?
4) What is the spatial distribution of corn yield growth rates, and how have these changed in a space–time context?
5) What impact has irrigation had on corn yield variability, growth rates, and absolute yield values in the Great Plains?
6) Which regions are potentially the most important to future food security in terms of experiencing the least significant interannual variation in corn yield (historically) and having a significant yield gap to exploit?

The bottom line is to illustrate temporal changes in yield variability and yield gain (or loss) trends across the U.S. Corn Belt during the twentieth century.

2. Approach and methods

We studied temporal changes and spatial distributions of corn yields for 13 major U.S. corn-production states, referred to as the Corn Belt,[1] for the period 1910–2001 using USDA–NASS county-level data. The yield data used in the composite analysis were the reported mean corn yields (e.g., the sum of the total production of irrigated and nonirrigated land divided by the sum of the areas, reported in

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[1] In this study, the Corn Belt specifically refers to the states of North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana, Ohio, and Kentucky.

bushels per acre), available from the USDA–NASS Web site (http://www.usda.gov/nass/). According to Prince et al. (Prince et al. 2001), county-level yields are determined after statewide yields are calculated, which are determined using a combination of random destructive sampling in field plots and a series of farmer interviews throughout the growing season. Randomly selected farmers in each county, which originate from the same set of farmers used to derive statewide yield values, are interviewed at the end of the growing season for yield and area planted information (Prince et al. 2001). The reader is referred to Prince et al. (Prince et al. 2001) for a more complete description of the calculation of county-level yield information.

The length of county-level corn yield records differed significantly among the states analyzed in this study (Table 1). Nebraska had the longest length of record at greater than 90 yr (starting in 1910), while Kansas only had a 40-yr record. Some counties had individual years that had missing data within a longer-term (>30 yr) record. In these few cases, the previous year's yield value was used as a surrogate and substituted.

To calculate annual-average corn yield growth rates and deviations from normal, we first estimated a long-term average (or "fitted yield") for the county-level yield data. To do so, we used single spectrum analysis (SSA), a type of principal component analysis that is suitable for short time series with significant interannual variations (Dettinger et al. 1995; Schlesinger and Ramankutty 1994; Botta et al. 2002). SSA decomposes data into trends, oscillatory components, and noise,

Table 1. Beginning year of USDA corn yield data reporting by state.

State	Yr
Nebraska	1910
Ohio	1918
North Dakota	1919
Missouri	1919
Minnesota	1921
South Dakota	1924
West Virginia	1924
Illinois	1925
North Carolina	1925
Iowa	1926
Wisconsin	1928
Indiana	1929
Kentucky	1929
Oklahoma	1933
Alabama	1939
Michigan	1942
South Carolina	1944
Mississippi	1953
Georgia	1954
Tennessee	1955
Kansas	1958
Virginia	1958
Louisiana	1959
Arkansas	1961
Colorado	1963
Texas	1968

and is superior to linear, quadratic, or any similar standard trend-fitting technique because it uses data-adaptive filters to extract information from the data rather than assuming a particular form a priori. In general, the most significant eigenmodes from SSA represent low-frequency variability. In our case, the first two modes generally accounted for 70%–80% of the total variability, and their sum is chosen as the fitted yield value; this value includes the influence of both technological changes and shorter-period (~5 yr) climate trends. We note, however, that some regions had a lower percentage of the total overall variability explained by the first two modes.

Absolute yield growth rate (in units of kilograms per hectare per year) was estimated as $T_t – T_{t−1}$ and the annual percent yield growth rate for each county was computed as $(T_t – T_{t−1})/T_{t−1} \times 100$, where T is the SSA fitted yield value and subscripts t and $t−1$ represent the current and previous year, respectively. The percent deviation from the fitted yield (yield residual) for each year was calculated by $(Y_t – T_t)/T_t$, $\times 100$, where Y represents the actual county yield. In the analysis of yield growth rates, we compared both percent changes (relative to the fitted yield) and absolute changes (in kilograms per hectare). While percent changes in crop productivity per units of land area are sometimes reported in the literature at the country or global scale, these values do not offer the best comparison across larger regions that have varied average yields. For example, a 1% annual-average growth rate within a county that has an average yield of 12 T ha^{-1} had a similar increase in grain (kilograms per hectare per year) as a 4% annual growth rate for a county averaging 3 T ha^{-1}.

3. Results and discussion

3.1. Trends and variability in long-term national corn yield data

We obtained historical track records of national-level corn yields from 1866 to 2002 from USDA–NASS (USDA–NASS 2003). We performed SSA on this dataset to identify the long-term changes (Figure 1). The fitted yield line shows that yields remained constant at approximately 1.6 T ha^{-1} (25 bu ac^{-1}) from the beginning of the record until the late 1930s. Our SSA detected only a very small decrease in absolute yields during the Dust Bowl era of the 1930s, when corn yields in the Great Plains and the Midwest were decimated by the persistent hot and dry conditions. From the 1940s onward, corn yields increased rapidly, increasing by a factor of 5 by the end of the twentieth century. However, relative growth rates of corn yield reached a peak of about 5% yr^{-1} during the 1960s, and have been declining ever since (Figure 2).

Variability in corn yield at the national level has been fluctuating widely during the past 140 yr, although showing a slight decrease (slope of trendline = –0.0136) over the whole time period (Figure 3), which agrees favorably with a previous analysis by Reilly et al. (Reilly et al. 2003). Variability (defined as the percentage absolute deviation from the fitted yield) was highest in the 1890s, when the percent deviation was 10%–12% greater than the fitted yield line (Figure 3); however, yields were also very low during that time (Figure 1). The next time period of increased variability was seen during the Dust Bowl era of the 1930s. The late 1950s to early 1960s were a period with relatively low variability in yield

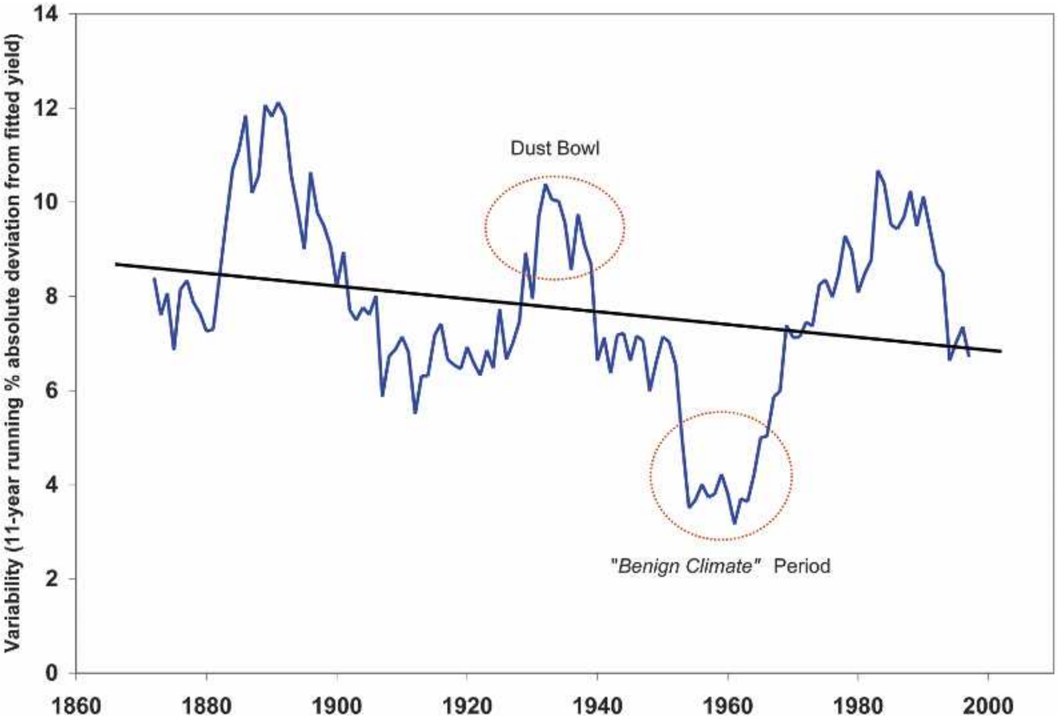

Figure 3. Statistical 11-yr running mean of the absolute percent deviation from the trendline for U.S. national corn yield data. The year plotted on the *x* axis represents the midpoint of the 11-yr time series (5 yr on either side of the middle year are used in forming the average).

(Figure 3), relatively higher yield values (Figure 1), and also high growth rates in yield (Figure 2). Indeed, from the mid-1950s to early 1970s, researchers have made reference to a period of "benign climate" when interannual variability in weather appeared to be diminished and favorable to reducing crop yield variability (Baker et al. 1993). Variability in corn yield has increased since the 1960s (Figure 3), whereas growth rates have decreased (Figure 2). However, since the mid-1980s, overall yield variability decreased through 2002 (Figure 3).

Naylor et al. (Naylor et al. 1997) suggested that the so-called benign period from the late 1950s to the early 1970s was a result of variability being masked by rapid advances in technology and increases in absolute yields. However, we feel that this is not the case because our estimate of variability is measured as a deviation from the fitted yield line, and hence the effect of any trend has effectively been removed. Naylor et al. (Naylor et al. 1997) and Reilly et al. (Reilly et al. 2003) also suggested that corn yield variability has increased significantly in the United States since 1950. The Naylor et al. (Naylor et al. 1997) study showed that in the 1950s, average annual deviation of yield (from the statistically fitted line) was 5.0%, and has increased steadily to 15.2% in the 1983–93 period. Reilly et al. (Reilly et al. 2003) reported an increasing trend in yield variability from 1950 to 1994 of 0.0236. The bottom line was yield variability at the end of these records in each study (1994) was significantly higher than at the beginning (1950). Our results agree with these previous analyses, although we find that yield variability has once again decreased since the mid-1980s.

3.2. Regional trends in yield variability at the county level: 1930–2001

One objective of this study was to use corn yield information at the county level to study the spatial patterns of these reported yields. We were also interested in verifying whether reported trends of increasing yield variability from 1950 onward (Naylor et al. 1997; Reilly et al. 2003) were detectable if county data prior to 1950 were included in the time series analysis. All Corn Belt states, excluding Michigan, Kansas, and a small portion of eastern Kentucky, reported county-level yield data that extended back to approximately 1930 or beyond (Table 1), giving us a larger time period to better understand whether increasing trends in crop yield variability may be largely due to natural climatic fluctuations, or potentially an artifact of increasing technology, approaching yield ceilings, or reliance on agrochemicals (pesticides and fertilizers).

Within states that had yield records dating back to 1930 or earlier, results suggested that only a small percentage of the total land area (~15%) in the study region had significant ($P < 0.05$) trends of increasing absolute yield variability. Figure 4a shows that across the states that had county records extending back to 1930 or beyond and have not relied on irrigation, there were only a few localized regions (southwest Illinois, north-central Iowa, north-central Indiana, and southeast Wisconsin) that had a significant ($P < 0.05$) detectable increasing or decreasing trend of interannual yield variability. Based on the slope of the linear regression performed on absolute values of yield residuals (Figure 4b), the regions in Illinois, Iowa, and Indiana have had a decreasing trend in yield variability since 1930, leaving only much smaller locales (such as southeast Wisconsin) with significant increases in variability from 1930 to 2001. Regions that showed a significant, decreasing trend of interannual yield variability could be attributed to large interannual variations during the Dust Bowl era of the 1930s that diminished significantly in the 1950s and beyond.

Widespread areas throughout South Dakota and Nebraska had significant ($P < 0.01$), negative trends in yield residuals (the slope of the linear regression was -0.25% to -2% yr^{-1}), primarily because the widespread introduction and increasing usage of irrigation in the late 1940s to early 1950s has significantly decreased interannual yield variability (Figure 4b). The average annual absolute deviation from the fitted yield line has decreased from 30% to 35% in the 1930s and 1940s to currently less than 15% in Nebraska.

In terms of long-term average absolute annual deviations from fitted yields during the entire data record (Figure 4c), areas in southern Minnesota and Wisconsin, northern Illinois, and southeast Ohio have had the least amount of overall interannual variability, generally between 8% and10%, and this increases significantly in westward and southward directions into Missouri, western Iowa, northwest Minnesota, and the Dakotas where average annual variability during the period *averages* between 14% and 30%. This is likely due to significant decreases in precipitation amount and increasing interannual variability during the growing season from an east to west gradient across the Corn Belt (Huff and Neill 1982).

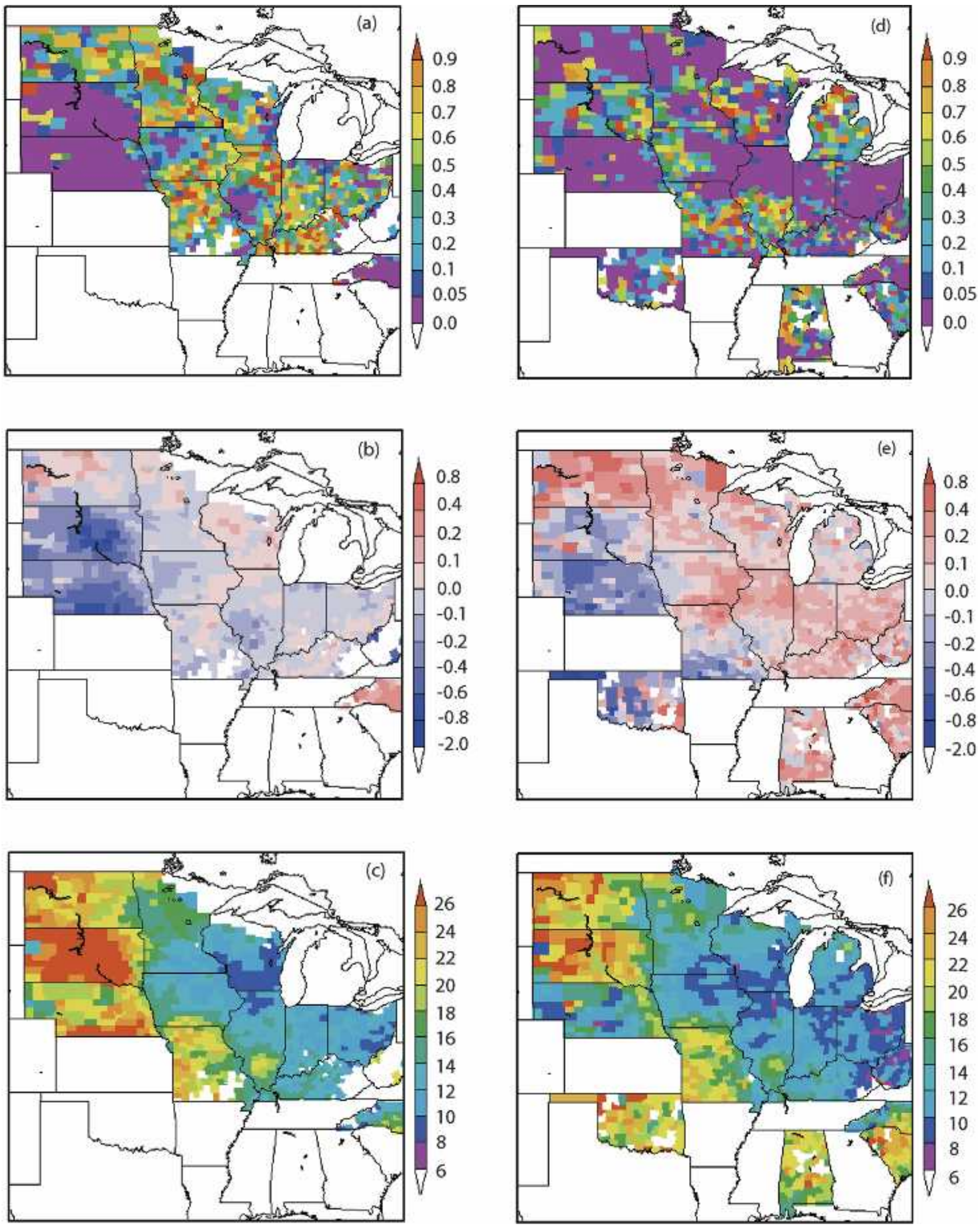

Figure 4. (a) The *P* value (statistical significance) of linear regression analysis performed on yield deviations (absolute values) from the SSA-fitted yields for each county that had data reported during the 1930–2001 time period; (b) slope of the linear regression analysis performed in (a); (c) the average absolute percent deviation from the fitted yield line for each county during 1930–2001; (d) the *P* value (statistical significance) of linear regression analysis performed on yield deviations (absolute values) from the SSA-fitted yields for each county that had data reported during the 1950–2001 time period; (e) slope of the linear regression analysis performed in (d); and (f) the average absolute percent deviation from the fitted yield line for each county during 1950–2001.

This analysis suggests that these regions of low interannual variability (e.g., southern Minnesota, northeast Iowa, Wisconsin, northern Illinois) are of particular importance to future food security as they exemplify the region of the U.S. Corn Belt that experiences the least amount of year-to-year variability in yield that is situated in the core region of the highest U.S. corn production (Figure 5).

3.3. Regional trends in yield variability at the county level: 1950–2001

In support of the conclusions of Naylor et al. (Naylor et al. 1997) and Reilly et al. (Reilly et al. 2003), we found that a much higher percentage of agricultural land area (~65%) in the Corn Belt showed significant ($P < 0.05$) trends of increasing interannual corn yield variability when the analysis of USDA data was confined to the 1950–2001 time period (Figure 4d). Much of the northern and central portions of Illinois, the majority of Indiana and Ohio, eastern Iowa, and portions of Wisconsin and Minnesota have had a significant increase in absolute yield variability

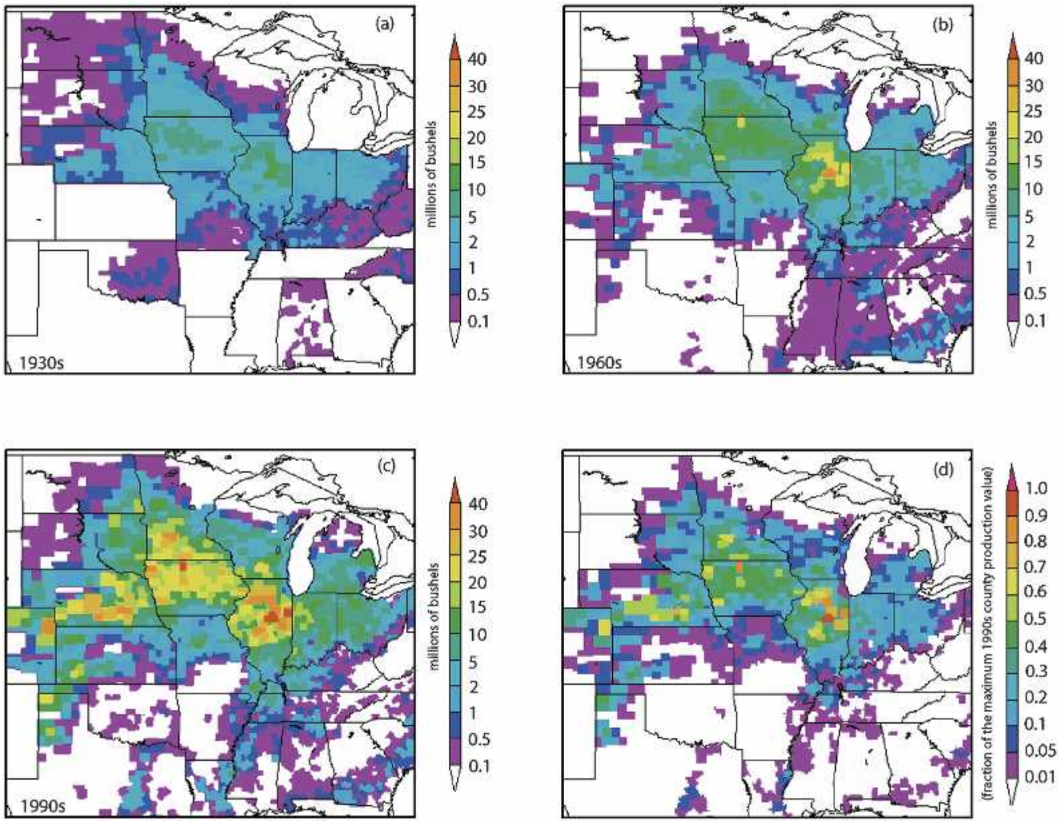

Figure 5. Annual-average corn production (millions of bushels) reported by the USDA for each county during the (a) 1930s, (b) 1960s, and (c) 1990s. (d) Annual-average corn production for each county during the 1990s divided by the maximum average county production value for the 1990s (McLean County, IL).

since 1950. However, the isolated small region of southern Illinois, which had a significant trend of increasing variability for the entire record (1930–2001), did not prove to be significant within the 1950–2001 time period. In addition, the central portions of South Dakota that had a statistically significant decreasing variability trend in the 1930–2001 analysis was not significant in the 1950–2001 time frame.

Since 1950, the majority of North Dakota, Minnesota, Wisconsin, Iowa, Illinois, Michigan, Indiana, Kentucky, and Ohio have seen an annual trend of increasing variability of between 0.05% and 0.6% yr^{-1} (Figure 4e). Only significant portions of southern Missouri, Oklahoma, Nebraska, and South Dakota have experienced decreased interannual variability since 1950, with linear trends averaging about −0.05% to −1.0% yr^{-1}. Figure 4f highlights the regions of the Midwest and Great Plains that have had the highest and lowest magnitude of variability since 1950; namely, Ohio, Indiana, southern Michigan, southern and central Wisconsin, northern and central Illinois, northern Iowa, and southern Minnesota, which have had the lowest annual-average yield residuals (~7%–12%). In contrast to our analysis over the 1930–2001 period when absolute variability over central Nebraska was 20%–30% (Figure 4c), mean variability dropped significantly to around 10%–15% for the 1950–2001 time frame (Figure 4f). Most of Missouri and North and South Dakota appear to be relative hotspots where variability has been the highest for the previous 70 yr, dating back to the Dust Bowl years of the 1930s (Figures 4c,f). However, the contribution of these areas to the overall U.S. corn yield volatility may be quite small because these areas have had historically low corn production (Figure 5).

The conclusions from the county-level analysis are substantiated by the temporal patterns of variability seen in the overall national totals (Figure 3). Variability decreased from the 1930s to the 1950s, but increased again after that. As is clear from Figure 3, an analysis of trend in variability from 1950 to 2001 will show a much larger increase in variability than an analysis from 1930 to 2001.

3.4. Decadal-scale changes in yield variability across the Corn Belt

We partitioned the 1930–2001 time period into seven decades, starting with the 1930s and ending with the 1990s (which extended into 2001) and analyzed the magnitude of changes in variability and their spatial distribution. We formed decadal averages of absolute percentage deviations from the average fitted yield for each 10-yr period (except the 1990s, for which we used the 11-yr period, 1991–2001) for each county. Only counties with data reported each year during each specific time frame were used in this part of the analysis. For example, several counties in northern Michigan, Wisconsin, and Minnesota stopped reporting county corn yield information in the late 1980s and therefore do not appear as part of the statistical analysis in later periods.

To best depict significant decadal changes, we chose to present three specific time periods as illustrations (figures). The 1930s (Figure 6a) and 1960s (Figure 6b) were chosen to show significantly contrasting results to contemporary patterns (Figure 6c). In general, the tranquil period or so-called benign climate era (Baker et al. 1993) of the 1950s–60s is particularly evident. A significant portion of the most productive region of the Corn Belt (Figure 5b) was only experiencing annual-average deviations of 2%–6% (absolute) from the fitted yields (Figure 6b) during

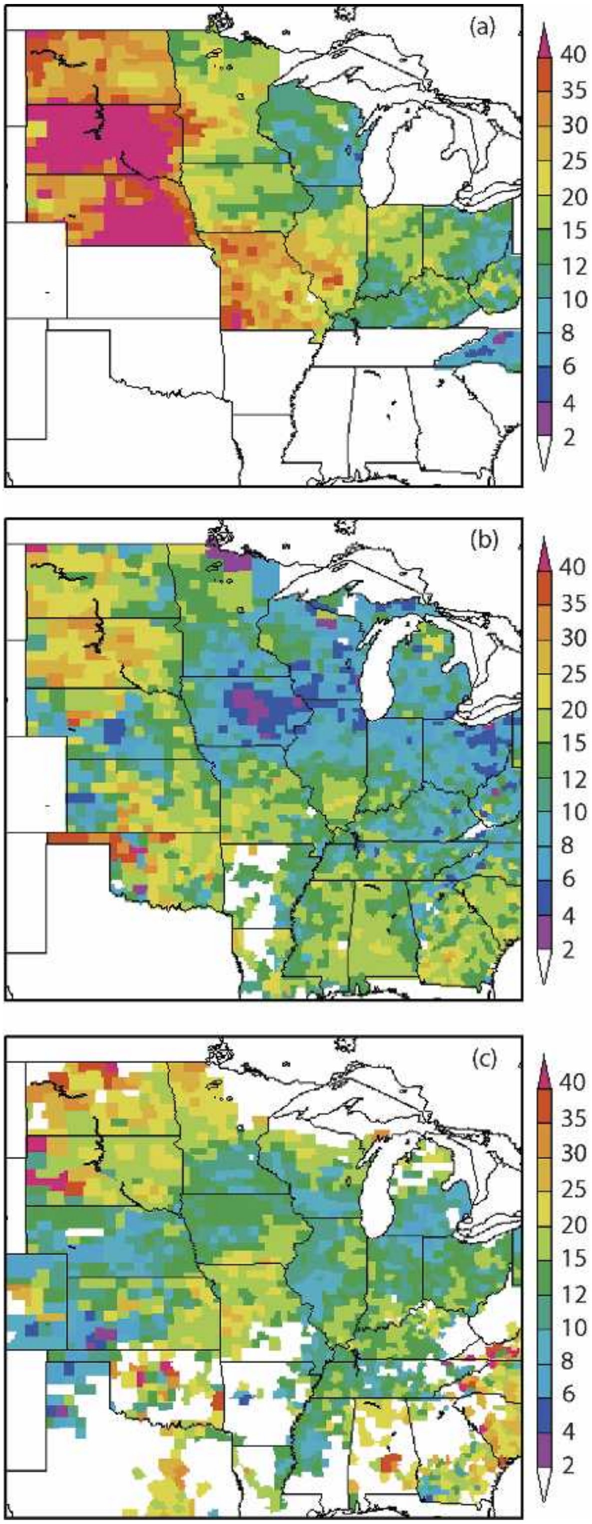

Figure 6. The average absolute percent deviation from the fitted yield line for each county for (a) 1931–40, (b) 1961–70, and (c) 1991–2001.

the 1960s, which was the lowest for any of the decadal-scale time periods examined in this study. This pattern was centered in Iowa, and extended into southern Wisconsin, Minnesota, northern Indiana, and Ohio. Portions of North and South Dakota have consistently experienced the highest levels of interannual variability, regardless of the decade.

While the 1930s were particularly devastating to agriculture in the Great Plains, a region where interannual variability was generally greater than 40% (Figure 6a), southern portions of Wisconsin and northern Illinois appear to have escaped devastating yield losses during this time (Figure 6a). We note that across Missouri, the only decade when absolute deviations were less than approximately 15% was during the 1960s; before and after this short time frame, variability is at least double, particularly in the northern portion of the state where the highest concentration of harvested acreage and cropland is located (USDA–NASS 2003; Donner 2003).

We defined deviations from the trend to be significant (not in a statistical sense, but in the sense of being large) when yields were ±20% from the SSA-fitted yield value for any year. When patterns of significant (±20%) deviations were studied between decades (not shown), we found that a large portion of Iowa, Minnesota, Wisconsin, Illinois, Indiana, and Ohio did not have any years in which yield deviated more than 20% (positive or negative) from the fitted yield values during the 1950s and 1960s. This trend carried into the 1970s in Ohio and was evident across Wisconsin during the 1940s. A rapid decrease of large interannual deviations took place across Nebraska from the 1940s to the 1980s, and across Kansas from the 1960s to the 1990s. When irrigated land area reached a maximum during the 1980s across Nebraska, large deviations (greater than 20%) were completely absent from the record. This pattern is still present in the contemporary era (Figure 6c) in heavily irrigated counties of the Great Plains region (e.g., central Nebraska, southwest Kansas, and the Texas Panhandle).

3.5. Positive versus negative average deviations and frequency of significant deviations

For each decade, we calculated histograms showing the fraction of county years falling within different bins of yield residuals, to show how percent deviations from fitted yields have changed temporally across the Corn Belt (Figure 7). The total number of data points or county years of data for each decade was equal to the number of counties multiplied by the total number of years in each averaging period.

While these histograms appear to approximate a normal distribution, the results suggest that a lower percentage of counties (frequency) have had negative deviations that were larger in magnitude than positive departures from the fitted yield lines. There are obvious shifts in the histograms as a function of each decade. In the 1950s, 76% and 48% of all county years had average absolute deviations of 20% or less and 10% or less, respectively (Figure 7). No other decade had a higher percentage of county years in these categories, again demonstrating a decade in which corn yield variability was at a minimum. In comparison, during the Dust Bowl era of the 1930s, approximately 28% of all county years had negative departures of −20% or greater, with 12% of county years having average depar-

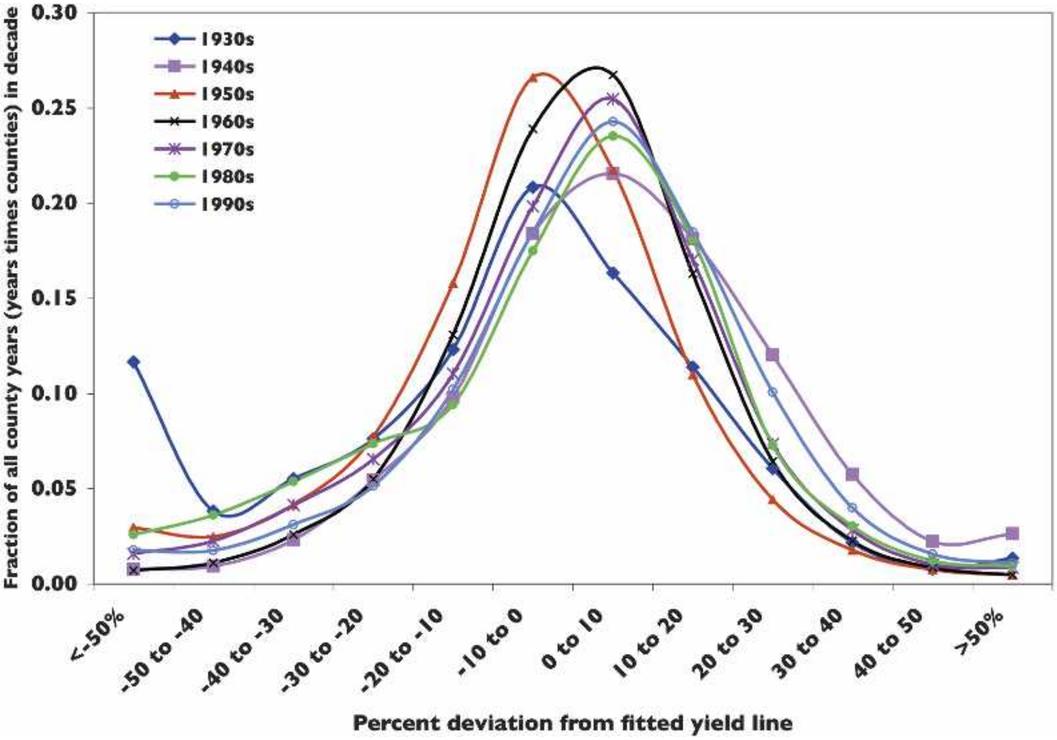

Figure 7. Histogram of the frequency of county yield residuals, categorized as a function of deviation magnitude (%) and decade.

tures greater than −50%. Overall, during the 1930s, 61% of all county years had a departure from the fitted yields that was negative. In contrast, the 1940s brought a dramatic shift to the below-average yields of the 1930s as only 38% of all county years had departures that were below the fitted yield lines. In general, the 1970s–90s have had similar distributions; approximately 25% of all county years in any given year during the past 30 yr experienced negative departures less than −10%, and about 15% of all county years had departures of −20% or less. However, on the positive departure end, only 10% and 5% of all county years in any year generally can expect positive departures of greater than 10% and 20%, respectively (Figure 7). For any given decade, only about 1% of all county years experienced a positive deviation from the fitted yield line of greater than 40%.

Because negative deviations from the SSA-fitted yield lines happen less frequently in the majority of counties, average negative deviations are larger in magnitude than positive anomalies. The exception to this generalization is across portions of South Dakota, Kansas, Oklahoma, and the southeast United States where the county's ratio of the total number of years that had positive versus negative deviations was between 0.4 and 0.45 (Figure 8). Based on how SSA removes low-frequency patterns of yield in calculating each county's fitted yield line, if the frequency of positive deviations from the fitted yield line is higher than negative departures, mathematically speaking, their average values must be smaller in magnitude. Figure 9 depicts the difference in absolute magnitudes

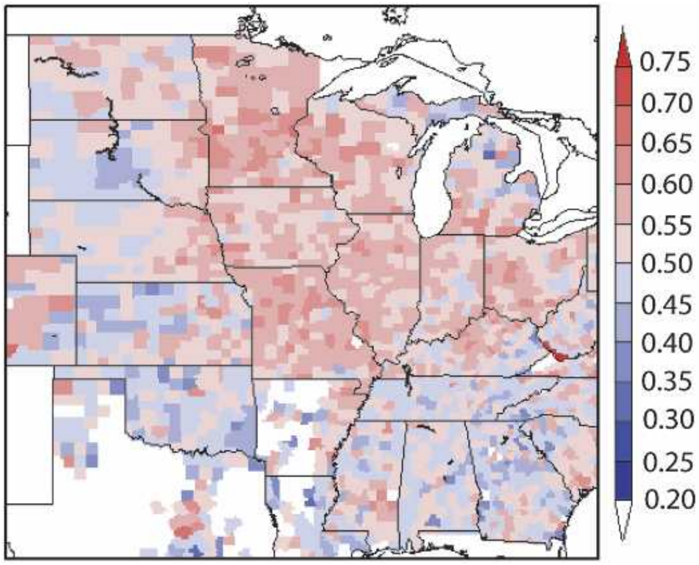

Figure 8. The fraction of years in each county's corn yield data record in which the deviation from the fitted yield line was positive.

between positive and negative deviations. The gradation of blue color depicts regions that have had average negative departures greater in absolute magnitude than positive departures. Thus, for any random year, the majority of the Corn Belt has average negative deviations that are 2%–15% greater (in absolute value) than

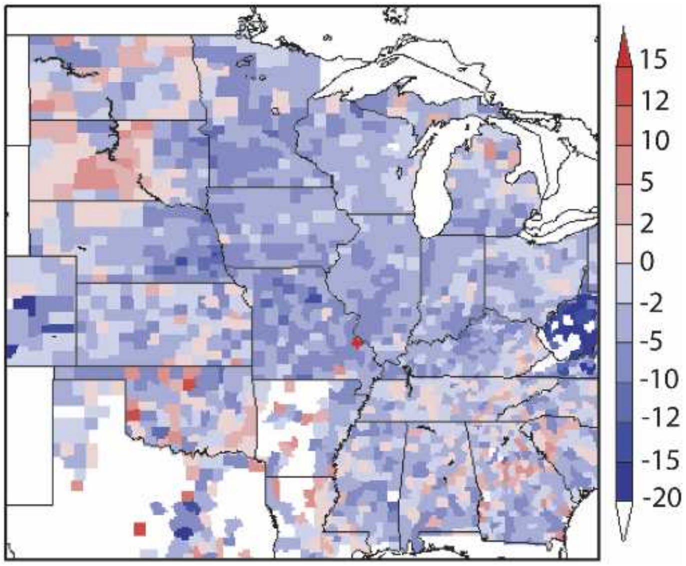

Figure 9. The absolute difference between the average positive and negative yield deviations (positive − negative, both treated as positive values) for each county over the complete corn yield data record.

positive values. The one region of exception is within the Dakotas where in some counties, positive deviations have averaged about 2%–7% higher than negative departures.

Our analysis suggests that over large portions of Ohio, Indiana, Illinois, Wisconsin, Iowa, and southern Minnesota, farmers experience large, significant (−20%) departures from the normal average yields (Figure 10a), and potential significant economic losses once every 10 yr (10% likelihood), on average. How-

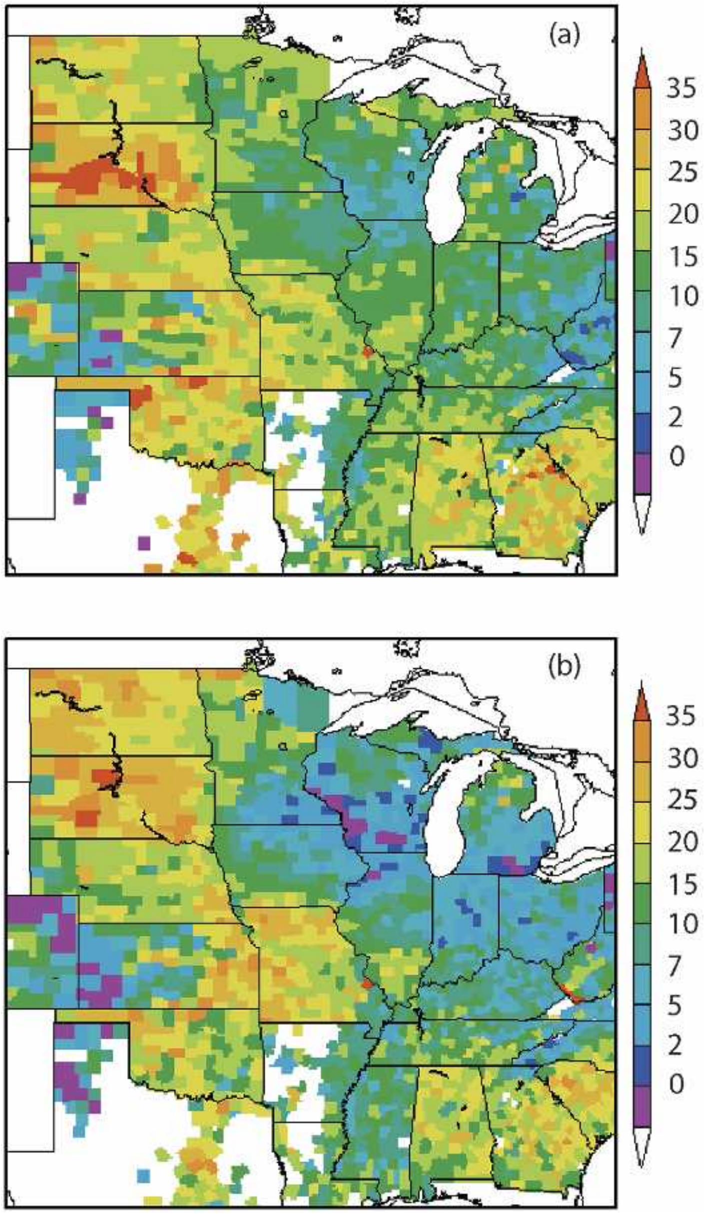

Figure 10. The percentage of all reported years for each county that had yield residuals that were (a) less than −20% and (b) greater than 20%.

ever, over the same region, significant gains (+20%) in productivity above the fitted yields occur only once every 15–20 yr (5%–7% likelihood; Figure 10b). In some counties of northern Illinois, far southern and western Wisconsin, southeast Michigan, Colorado, Kansas, and Texas, there were no occurrences when county yields have been greater than 20% above the fitted yield curve (Figure 10b). Thus, according to the record, the tendency is for farmers in those counties to experience more frequent, smaller positive deviations from their overall average, expected yields; however, this is potentially offset by less frequent but more catastrophic yield losses.

3.6. Impacts of irrigation in the Great Plains: Trends in overall yield and stability

We performed a more detailed analysis of corn grown for grain in two Great Plains states (Nebraska and Kansas) because our larger regional study suggested that significant changes to yield stability have occurred in these western portions of the Corn Belt. Furthermore, these are two of the most highly irrigated regions in the United States. In particular, approximately 60% of maize grown today is irrigated in Nebraska and current county-average yields rank toward the top of the U.S. distribution in Nebraska, and a few counties in Kansas (Gray and Haskell) are nearing the 190 bu ac^{-1} threshold. Furthermore, SSA-fitted values of county maize yield suggest a plateauing or even a slight decrease in fitted yields during the past 10–15 yr in some counties within these two states.

Irrigated and nonirrigated county corn yield data were studied for Nebraska during the 1947–2001 period. In general, a significant increase in the percentage of total irrigated maize harvested has taken place since the early 1950s. The ratio of irrigated area to total area (maize grown) peaked at about 70% in the early 1980s and remained constant until about the mid-1990s. Since then, a steady decrease has taken place to a level around 60% in 2001. Maize production on irrigated land as a ratio of the total production peaked at 80% in the early 1980s, and is now at about 70% (USDA–NASS 2003).

Figure 11 shows the state-average yield residuals for both Nebraska and Kansas. We applied SSA to the state-average yield for each year separately for irrigated and nonirrigated corn. The long-term average absolute deviation was 6.1% and 6.4% for Kansas and Nebraska irrigated corn during each state's period of record, respectively, but 21.1% and 19.0% for Kansas and Nebraska rain-fed corn, respectively. The magnitudes of average positive versus negative deviations from the fitted yields were comparable in both states (5.6% and −7.4% in Nebraska and 5.8% and −6.5% in Kansas for irrigated fields, and 18.5% and −19.7% in Nebraska and 21.1% and −21.0% in Kansas for rain-fed fields). These results show that irrigation has significantly reduced corn yield variability in these regions by about a factor of 3. Irrigated fields have experienced year-to-year fluctuations in corn yield that are only 30% of the magnitude of those seen within rain-fed fields. There were no significant increases or decreases in interannual variability when state-average yield residuals for irrigated versus rain-fed corn were analyzed independently ($P \ll 0.0001$).

These data illustrate how these important, historical corn-production regions (Figures 5a–c) are at a high risk for diminishing returns if more stringent rules are

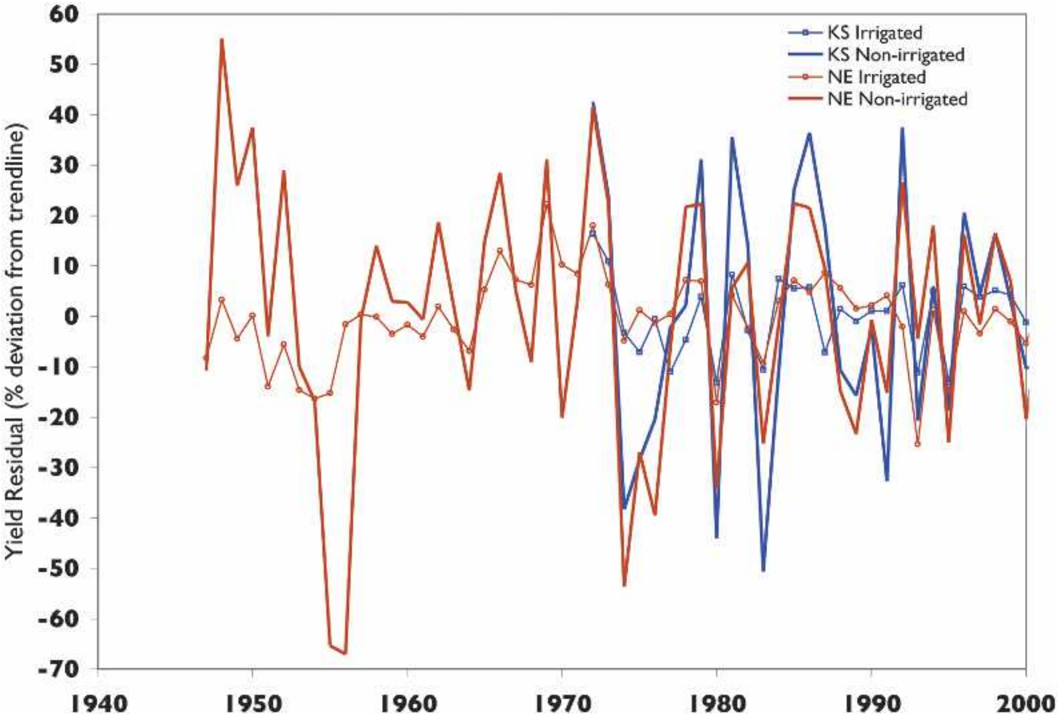

Figure 11. The annual state-average corn yield residuals (from SSA) for irrigated and nonirrigated corn grown for grain in Nebraska (red) and Kansas (blue).

placed on irrigation and if growing season precipitation decreases as it did during the Dust Bowl. Figure 5d illustrates that many counties of central Nebraska along the Platte River and counties of central and southwest Kansas have had annual-average production during the 1990s that was 40%–70% of the highest corn production county in the United States (McLean County, Illinois). Today, if devastating drought conditions persisted and water withdrawal from aquifers for irrigation purposes was banned, corn yields could potentially decrease by 3.8 Mg ha^{-1} in these regions (e.g., the difference between an average of 8.8 Mg ha^{-1} for irrigated corn versus 5.0 Mg ha^{-1} for rain-fed corn). Figure 12 shows the difference between rain-fed and irrigated corn yields at the state level in Nebraska from SSA. While irrigated corn yields are 76% higher today than rain-fed corn, the yield gap has remained constant since 1975.

3.7. Analysis of county-level yield trends: Rate of annual increases from 1930 to 2001

We used the SSA-fitted yield values for each county to calculate the annual growth rate or change in annual-average yield according to the fitted value for each county. We investigated how the magnitude of corn yield growth has varied with time during the twentieth century, and how it has varied spatially across the

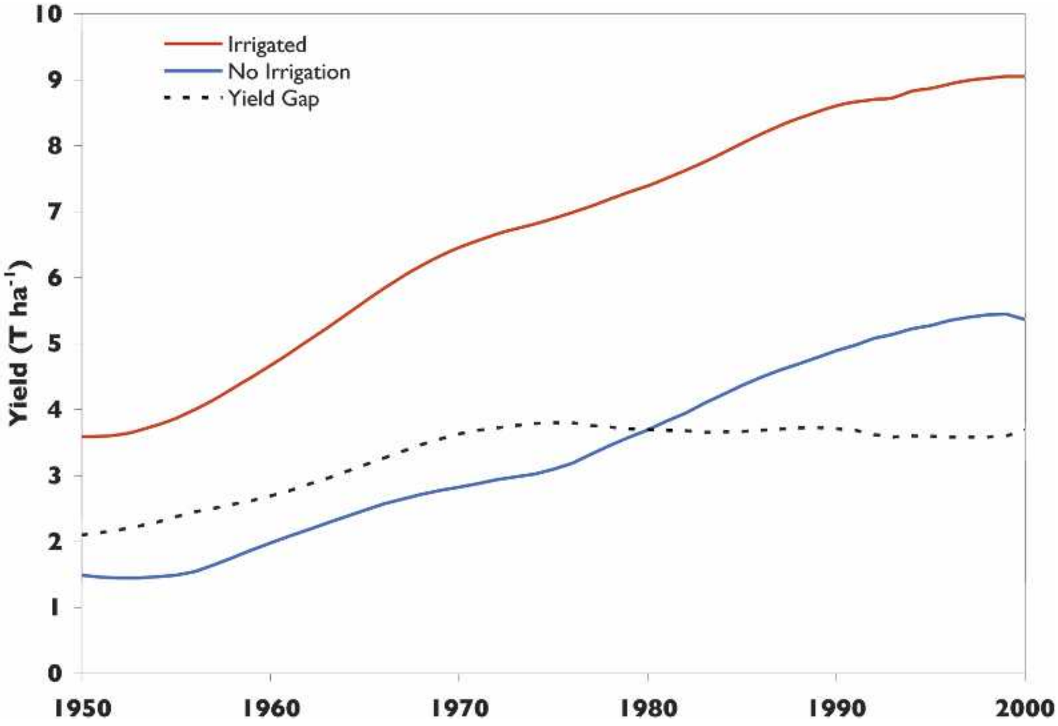

Figure 12. The state-average fitted corn yields (from SSA) for irrigated and nonirrigated corn grown for grain in Nebraska and the corresponding yield gap.

Corn Belt. We also formed decadal averages (e.g., 1931–40, 1941–50, 1951–60, 1961–70, 1971–80, 1981–90, 1991–2001) to help visualize changes in a space versus time context. While increases in yield were quite uniform across the Corn Belt in the 1930s (Figure 13a) and 1940s, averaging between −25 and 100 kg $\mathrm{ha^{-1}}$ $\mathrm{yr^{-1}}$, the 1950s and 1960s brought much more rapid grain increases in Nebraska, Kansas, Iowa, and central Illinois, and to a lesser degree across Kentucky, Indiana, Ohio, and Wisconsin (Figure 13b). Annual yield growth rates within the irrigated portions of Kansas and Nebraska approached 250 kg $\mathrm{ha^{-1}\ yr^{-1}}$ in the 1960s, and between 125 and 225 kg $\mathrm{ha^{-1}\ yr^{-1}}$ in Iowa, Illinois, and Indiana. The average county corn yield across the entire study region was increasing only by 18.2 kg $\mathrm{ha^{-1}\ yr^{-1}}$ in the 1930s, but peaked at 124.5 kg $\mathrm{ha^{-1}\ yr^{-1}}$ in the 1960s. During the 1960s, only 2% of all county years had decreasing average yields according to the SSA-fitted yield values in our study, whereas in the 1990s, 17% of all county years suggested a stable or decreasing average corn yield (Figure 13c). From the 1970s to the 1990s, the annual-average increase in SSA-fitted yields at the county level had decreased from 106.3 to 49.2 kg $\mathrm{ha^{-1}\ yr^{-1}}$.

The 1960s represented the period of most rapid growth in corn yield across the Corn Belt; 30% of all county years had annual-average yield increases of greater than 150 kg $\mathrm{ha^{-1}}$ (Figure 13b). Two significant changes are apparent in average-annual yield increases across the Corn Belt during the past 70 yr; from the 1930s

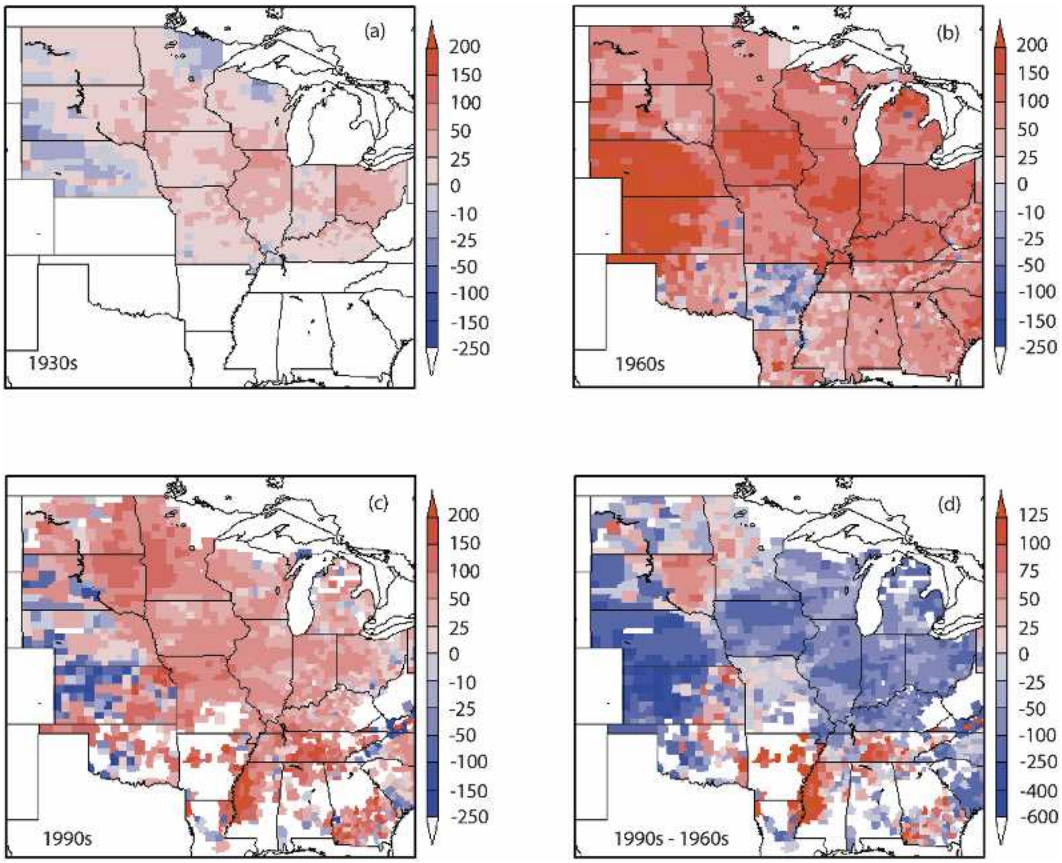

Figure 13. (a) Average yield growth rate (kg ha^{-1} yr^{-1}) during the 1930s for each county, calculated by performing differencing between successive years along each county's fitted yield line (from SSA); (b) same as in (a), except for the 1960s; (c) same as in (a), except for the 1991–2001 period; and (d) difference between 1991–2001 averages and the 1960s.

to the 1960s, yield growth rates were becoming increasingly higher. But, from the 1970s–90s, there is a definitive shift toward diminishing returns.

Today, the peak region of most rapidly increasing corn yield in the Corn Belt is centered in South Dakota and west-central Minnesota, and portions of eastern Kansas and Oklahoma, and also in Tennessee, Arkansas, and Mississippi farther south (Figure 13c). While approximately 50% of the Corn Belt has shown modest yield increases of 10–100 kg ha^{-1} yr^{-1} during the 1990s, significant portions of Kansas, Nebraska, South Dakota, and eastern Ohio have shown declining average yield during the 1990s (Figure 13c). Regions of Kansas and Nebraska, which had some of the highest annual-average yield increases 25 yr earlier (1970s), are now showing decreasing yield trends of –25 to –200 kg ha^{-1} yr^{-1}. When growth rates were compared between the 1990s and 1960s (Figure 13d), the trend of diminishing returns is widespread across much of the major corn-production regions (Figures 5c,d). In fact, the percentage of all county years with decreasing yield trends in the 1990s was 16.8%, which parallels the trends seen during the 1930s in which the value was 24.5%. For the 1940s–80s, the percentage of all county years in each decade with decreasing yield trends were between 1.1% (1960s) and 5.1% (1980s).

Several counties in Kansas and Nebraska that rely on irrigation appear to have reached a yield plateau, or have closed the yield gap. In general, state-average growth rates for irrigated maize in Nebraska peaked during the 1960s at approximately 200 kg ha^{-1} yr^{-1}, and then again in the 1980s at 150 kg ha^{-1} yr^{-1}. Nonirrigated maize annual yield growth rates were about 50% of irrigated maize in the 1960s, but as mentioned previously, have demonstrated equal gains since the 1970s (Figure 12). The yield gap between Nebraska state-average irrigated and nonirrigated maize increased linearly until about 1970, and has remained constant since then at 3700 kg ha^{-1}. However, the yield gap between irrigated and nonirrigated corn is largest in the western portion of the state (as high as 6300 kg ha^{-1} in some counties during the 1990s), and less in the east (as low as 1200 kg ha^{-1}) because of decreasing amounts of precipitation from east to west.

3.8. Relationship of decadal-average yields to changes in trend

We investigated the relationship between yield growth rates as a function of absolute yield averages for each decade. Many previous studies have recognized that it is becoming more difficult to maintain the large yield increases of the 1960s (Mann 1999), and that it may take a second coming of another agricultural revolution to boost yields so that average annual increases in grain production can keep up with an escalating demand for food. Here, we simply illustrate the general relationship between decadal-average yield values for each county versus the annual growth rate in yield expressed both in absolute terms (kilograms per hectare per year) and relative terms (percentage; Figures 14a,b). It appears that the window of greatest gain in yield was at a time when yields were averaging 3.8 Mg ha^{-1} (the 1960s). During this period, annual-average percent increases in yield, according to the SSA-fitted yield line, were as high as 13% in some counties, averaged 3.4% across the Corn Belt, and have not been equaled since that time. As absolute county-level corn yields have increased, the trend has been for diminishing returns, with an increasing number of counties having negative trends in absolute yield gains. Today, a considerable number of counties still show signs of positive annual growth in yield of between 25 and 100 kg ha^{-1} yr^{-1}, but this only represents a 0.78% annual-average increase.

4. Discussion and conclusions

We concluded that the choice of time period used for statistical analysis (either 1930 or 1950 to 2001) was important to conclusions drawn about twentieth-century trends in corn yield variability. Widespread increases in yield variability were statistically significant from 1950 onward, but were less obvious from 1930 to 2001. According to our statistical analysis of the aggregated U.S. corn yield values from 1866 to 2002, there are also indications that variability has decreased in magnitude from the early 1990s to 2002.

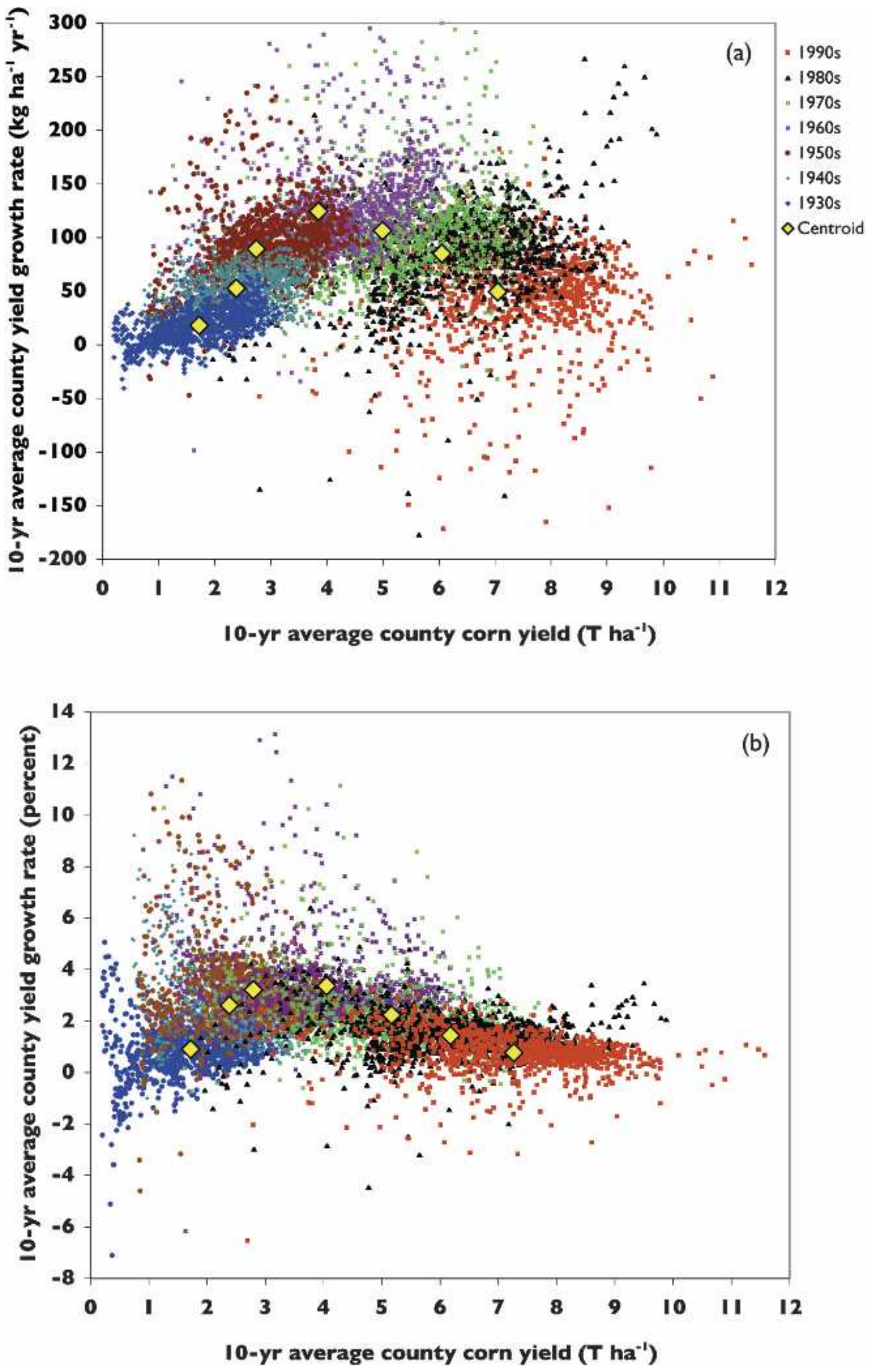

Figure 14. (a) Plot of decadal-average absolute yield growth rate for each individual county (from SSA-fitted yield line) vs the decadal-average county corn yield. (b) Plot of the decadal-average relative (normalized according to the raw yield average) yield growth rate for each individual county (from SSA-fitted yield line) vs the decadal-average county corn yield.

While widespread decadal-scale changes in corn yield variability and yield growth rates (based on long-term trends) have occurred since the 1930s across the Corn Belt, the response has varied considerably with geographic location. Northern portions of the Great Plains (e.g., North and South Dakota) have experienced consistently high interannual corn yield variability, averaging about 30%–40% relative to the mean. The increasing usage of irrigation across regions farther to the south from Nebraska to Kansas and Texas since the 1950s has helped boost yields by 75%–90% over dry land corn, creating a yield gap of 60–90 bu ac^{-1}. Irrigation has reduced interannual variability by a factor of 3 in regions that receive inadequate precipitation, generally west of the 500-mm annual precipitation isopleth.

We note, however, that there are other potential reasons (other than growing season precipitation variability) for the apparent "high" interannual yield variability across North and South Dakota, where average yields are 100–125 bu ac^{-1} less than in irrigated regions that receive similar amounts of precipitation (Figure 15). Across these dry, nonirrigated regions of the Great Plains, there is greater potential to boost yields above those in rain-fed fields in good weather years (e.g., sufficient or above-normal precipitation). Within irrigated fields of Nebraska and Kansas, excess rainfall may help to increase yields, but a combination of farmer management (when and how much to irrigate) and the fact that yield values are much higher translates into a more difficult scenario to boost yields that might already be approaching a yield ceiling. Thus, the very fact that a large yield gap is available to exploit in these regions (Figure 15) is one potential reason for the

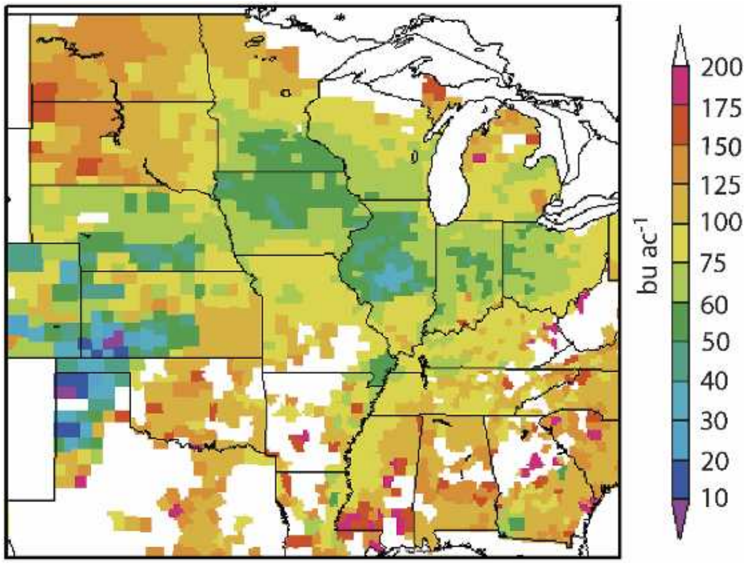

Figure 15. The difference (or yield gap) between each county's annual-average corn yield and the maximum U.S. county average (192.9 bu ac^{-1}) for the 1990s. The top three county corn yield averages for the 1990s were in heavily irrigated regions; Hartley County, Texas (192.9 bu ac^{-1}), Gray County, Kansas (185.2 bu ac^{-1}), and Haskell County, Kansas (183.6 bu ac^{-1}).

apparent increased, absolute variability. This hypothesis is substantiated by the fact that some portions of central South Dakota had average positive deviations above the fitted yield line that were 10% greater than negative anomalies (Figure 9), and occurred less frequently (Figure 8). This behavior is generally in contrast to that observed over the remainder of the Corn Belt. Furthermore, the fraction of land area that is devoted to corn in central South Dakota is only 1%–10% (Donner 2003). Thus, there may be more errors associated with forming a "true" average annual yield from less harvested acreage. Counties in this region had annual production in the 1990s that was only 1%–5% of the top producing U.S. county (Figure 5d). Therefore, the high level of variability across this region may have minimal impacts to overall food production in the future.

It appears that a larger region of eastern Iowa, southern Minnesota, southern Wisconsin, and northern Illinois represents an area of the Corn Belt that has experienced the least amount of interannual variability in rain-fed corn fields. Historically, during the twentieth century, the risk of significant crop failure has generally been the lowest in this specific region. Because counties in these regions are generally top producers for the United States (40%–90% of the top production value for the 1990s; Figure 5d) without the aid of irrigation, future climate change (e.g., drier conditions) in the region could significantly impact overall U.S. corn production. Therefore, this region is an area of prime agricultural real estate that may warrant protection from future changes in land use that may decrease the overall amount of land area devoted to crops here.

We suggest that there is still a significant yield gap of 30–75 bu ac^{-1} (Figure 15) to explore over the core Corn Belt region, based on growth rate trends and overall yields in irrigated regions (Figure 13). We calculated a yield gap for each county based on the difference between the maximum average county-level corn yield in the region for the 1990s (Hartley County, TX, 192.9 bu ac^{-1}) and each county's average yield value for the same time period. We assumed that the stabilization of yield increases across the heavily irrigated counties in Kansas, Nebraska, and northern Texas (such as Hartley County) were leading to a hypothetical maximum yield that could eventually be reached in other counties of the Corn Belt in the near future. While Figure 15 suggests that an even greater yield gap exists on the periphery of the core Corn Belt over such regions as northern Wisconsin and Minnesota, eastern North and South Dakota, eastern Kansas, and northern Missouri, there are other factors limiting corn yields and food production in these areas such as soil, climate, and ultimately economics that drive land-use decision making. Even though regions of the northern Great Plains appear to have a significant yield gap to explore, this potential will probably not be realized unless irrigation is an allowable avenue to continue to pursue indefinitely, or if significant changes to precipitation patterns across the region occur. The Great Plains region is generally too dry to match the current productivity of agricultural land farther to the east and south.

There is evidence of a general inverse relationship between absolute yield and absolute growth rate for yields above 4 T ha^{-1} (Figure 14a), although the exact relationship between these quantities is likely impacted by soil type, management, and climate. The relationship is obviously more apparent when yields are plotted against the percentage increase for each decade (Figure 14b). While the slope of the line that is fit to this relationship for the last four decades is negative, where (and if) it drops to zero in the future as yields go up is purely speculative. It is conceivable that the percentage growth could reach an asymptote at a small value as farmers continue to refine management. However, it is clear that the spectacular gains of the 1960s are over for the most part—only a few localized regions show signs of significant growth and these are regions where current yields are below the average when compared to the rest of the Corn Belt.

Based on some of the patterns uncovered in this research, we ponder how yields may continue to increase in the future. One key area that has the potential for improvement is in nitrogen fertilizer–use efficiency. Currently, nitrogen fertilizer–recovery efficiency is only 37% for north-central U.S. corn hybrids (Cassman et al. 2002), which is believed to be partially responsible for significant nitrate loading into waterways since the 1950s (Donner and Kucharik 2003). More dry matter production in the future will demand more nitrogen to produce it, but the addition of more nitrogen fertilizer to our soils and ecosystems have potentially devastating consequences to the overall environment and its future sustainability. Therefore, environmentalists would rather see increases in corn yield result from widespread farmer micromanagement (e.g., precision agriculture) of their farms (Mann 1999). If current farm management trends continued, yield increases could result from increased usage of irrigation and agrochemicals. However, because of the elevated risk posed to human health associated with the depletion and contamination of water supplies via irrigation practices and increasing agrochemical usage, emerging environmental protection laws could make future corn yield increases much more difficult.

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