Adapting to Climatic Challenges: A Progress Report on Studies of the Historical Evolution of Wheat Production

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Abstract: The historical record offers considerable insight into the adaptability of agriculture to climatic challenges. During the late 19th and early 20th centuries, farmers in the frontier regions of North America, Australia, and other areas to push wheat production into environments previously considered too harsh and variable to cultivate.

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In recent years, adverse weather shocks in the world's major wheat-producing regions have repeatedly sapped yields and output. Since 2003, much of Australia has experienced a long severe drought, with only limited spells of relief. Its grain crops have suffered. The Great Russian Heat Wave of 2010, in which summer temperatures exceeded anything observed in 130 years of record-keeping, ravaged its wheat crops and led to a ban on grain exports.[1] In the winter of 2010-11, a severe drought across the North China Plains-- purportedly the worst in two centuries-- endangered China's winter wheat crop.[2] In a globalized economy, local crises, even prospective crises, can have immediate worldwide impacts. Adverse shocks to expected grain supplies raise global prices, threatening the food security of inhabitants of developing countries and fueling political unrest.

A succession of weather-related harvest shocks has heightened concerns that global climatic change is making it harder to feed the world.[3] This has become a recurrent theme in the mainstream press, including the *New York Times*,[4] *Washington Post*,[5] and the *Economist*,[6] and leading academic journals. In an important recent article in *Science,* Lobell, Schlenker, and Costa-Roberts report that between 1980 and 2008, global warming has reduced wheat yields in

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[1] "Russia, Crippled by Drought, Bans Grain Exports," *New York Times*, 5 Aug. 2010.

[2] "Drought May Impact China's 2011 Winter Wheat Crop," *USDA Foreign Agricultural Service, Commodity Intelligence Report*, 14 Jan. 2011; "East China wheat basket braces for worst drought in 200 years," *People's Daily Online*, 8 Feb. 2011. Global grain prices jumped on such reports, even though crop yields depended greatly on rainfall occurring later in the spring.

[3] Global warming is, of course, not the only force driving up food prices. In the United States, the Energy Policy Act of July 29, 2005 (Pub.L. 109-58) mandated more biofuel be added to gasoline. Most was ethanol produced from maize. And in Uganda, a mutant to stem rust, Ug99, emerged as a new threat to grain production. Plant scientists are making progress developing wheats resistant to the new threat. Paul Voosen, "Scientists Breed Wheat 'Near Immune' to Devastating Plague," *New York Times*, 10 June 2011.

[4] Justin Gillis, "A Warming Planet Struggles to Feed Itself," *New York Times*, 5 June 2011, and "Reverend Malthus and the Future of Food," *New York Times*, 6 June 2011.

[5] "Global warming already crimping crop production, pushing prices higher," *Washington Post*, 5 May 2011; Rick Weiss, "Facing a Threat to Farming and Food Supply," *Washington Post*, 19 Nov. 2007, p. A06.

[6] "A special report on feeding the world: Our daily bread, Bringing wheat up to scratch," *Economist*, 24 Feb 2011; "Climate change and crops: Hindering harvests," *Economist*, 5 May 2011. Wheat is one of the Economist's pet topics; see "Ears of plenty: The story of man's staple food," *Economist*, 20 Dec. 2005 among many previous articles.

major producing countries by 5.5 percent and cut maize yields by 3.8 percent.[7] (The effects on yields of soybeans and rice were not significant to date and North American grain farmers have largely dodged trouble, at least for now.) Researchers at CIMMYT (International Maize and Wheat Improvement Center) have investigated how climate trends are altering the area suitable for grain production. One prominent study is provocatively entitled "Climate Change: Can wheat beat the heat?" They anticipate North America wheat farmers will have to cease production at the southern end of the grain belt but may be able extend cultivation 600-700 miles northward about 10 degrees latitude, from the current northern limit of production; see Figure 1. Alaska is projected to become a wheat growing region.[8]

To help understand the prospects for adapting to predicted climate change, this paper summarizes and supplements our long-run analysis of how farmers in the past learned to produce in unfamiliar and challenging environments.[9] We examine changes in wheat production, starting first in North America and then moving globally. We do not explicitly examine the responses to fluctuations over time in the climate at a set of fixed locations. Instead we seek insight by investigating the behavior of settlers moving climate-sensitive production activities to new locations, often to locations with significantly harsher and more variable environments. These

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[7] David B. Lobell, Wolfram Schlenker, and Justin Costa-Roberts, "Climate Trends and Global Crop Production Since 1980," *Science* 5 May 2011: 1204531Published online 5 May 2011 [DOI:10.1126/science.1204531] They find that, outside of the US, temperature trends between 1980 and 2008 have exceeded the one standard deviation of the annual variations. They model annual crop yields in a sample of major producing countries as a quadratic function of short-run temperature and precipitation variation, that is to say weather. Compared to a counter-factual world without climate trends, they find wheat yields were 5.5 percent lower.

[8] Rodomirio Ortiz, Kenneth D. Sayre, Bram Vovaerts, Raj Gupta, G. V. Subbarao, Tomohiro Ban, David Hodson, John M. Dixon, J. Ivan Ortiz-Monasterio, and Matthew Reynolds, "Climate change: Can wheat beat the heat?" *Agriculture, Ecosystems and Environment* 126 (2008): 46-58. Wheat will remain a viable crop in many areas of current production. According to this account, some of the winter wheat area will likely drop out (the light orange in Figure 1), but much will remain (the dark orange). See also Matthew P. Reynolds, Dirk Hayes, Scott Chapman "Breeding for Adaptation to Heat and Drought Stress" in Matthew P. Reynolds, (ed.), *Climate Change and Crop Production*,Wallingford, Eng.: CABI, 2010, pp. 71-91.

[9] This analysis draws on our published work, including Alan L. Olmstead and Paul W. Rhode, "The Red Queen and the Hard Reds: Productivity Growth in American Wheat, 1800-1940," *Journal of Economic History* 62:4 (Dec. 2002), pp. 929-966; "Biological Innovation in American Wheat Production: Science, Policy, and Environmental Adaptation," in Susan Schrepfer and Philip Scranton (eds.), *Industrializing Organisms: Introducing Evolutionary History*, New York: Routledge, 2003, pp. 43-83; "Biological Globalization: The Other Grain Invasion," in T. Hatton, K. O'Rourke, and A. Taylor, (eds.), *The New Comparative Economic History: A Volume Honoring Jeffrey G. Williamson,* Cambridge: MIT Press, 2007, pp. 115-40; *Creating Abundance: Biological Innovation and American Agricultural Development*, Cambridge: Cambridge University Press, 2008; "Adapting North American wheat production to climatic challenges, 1839-2009," *Proceedings of National Academy of Sciences*, Early (Online) Edition: December 27, 2010, doi:10.1073/pnas.1008279108; Print: January 11, 2011, 108 (2) 480-485; "Responding to Climatic Challenges: Lessons from U.S. Agricultural Development," in Gary D. Libecap and Richard H. Steckel, (eds), *Climate Change Past and Present: Uncertainty and Adaptation.* Chicago, Univ. of Chicago Press, 2011, pp. 169-194.

changes for the most part occurred before the advent of modern plant genetics. Our evidence says nothing directly about the ability of future farmers aided by rapid advances in plant sciences to respond to climatic changes, but the historical adjustment process does indicate that the malleability of the agricultural enterprise rendered obsolete the predictions of many past experts.

In the mid-nineteenth century John Klippart, of the Ohio State Board of Agriculture, was arguably the most informed individual in North America on wheat culture. In 1858 he published a 700-page tome detailing much of what was then known about the wheat plant and wheat farming around the world.[10] For the age this was a remarkable piece of scholarship. In his view agro-climatic conditions limited the permanent commercial wheat belt to the region between the 33rd and 43rd latitudes encompassing Ohio, the southern parts of Michigan and New York, Pennsylvania, Maryland, Delaware, and Virginia. The soils in the latter three states had been largely exhausted and without considerable investment in fertilizer, production would soon decline. Klippart was aware of the large increase in output to the west of Ohio, but he maintained that the soils and climates of Illinois, Iowa, and Wisconsin would doom those states to the haphazard production of low quality and low-yielding spring wheat. The region beyond the 98th parallel stretching from Lake Winnipeg through eastern Nebraska to Gulf of Mexico was mostly “an unproductive desert.” Rust infestations would forever limit production in the South. Unless the country husbanded its resources it would soon be an importer of wheat. Klippart (p. 323) argued that “Canada may be left out of the wheat region” due to declining productivity.

Figure 2 maps Klippart’s vision of the potential long-term wheat-producing area of the North America. Figure 3 maps the actual location of wheat production in 1919-20. Klippart proved so far off the mark because he failed to anticipate the biological innovations that would transform North American wheat production. And as impressive as the geographic spread of wheat production were the accompanying shifts in the ranges of growing conditions. According to Mark Alfred Carleton, a prominent USDA agronomist, the regions of North America producing wheat in the early twentieth century were as “different from each other as though they lay in different continents.”[11]

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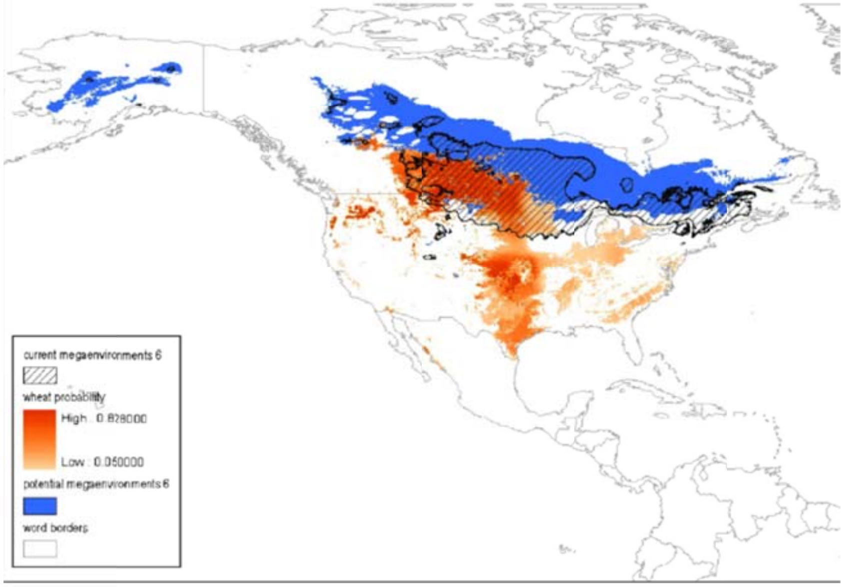
[10] John H. Klippart, *The Wheat Plant: Its Origin, Culture, Growth, Development, Composition, Varieties, Diseases, Etc., Etc*. New York: A.O. Moore & Company, 1860, pp. 296-327.

[11] Mark Alfred Carleton, *The Basis for the Improvement of American Wheats*, USDA Division of Vegetable Physiology and Pathology Bulletin, no. 24 (1900), p. 9.

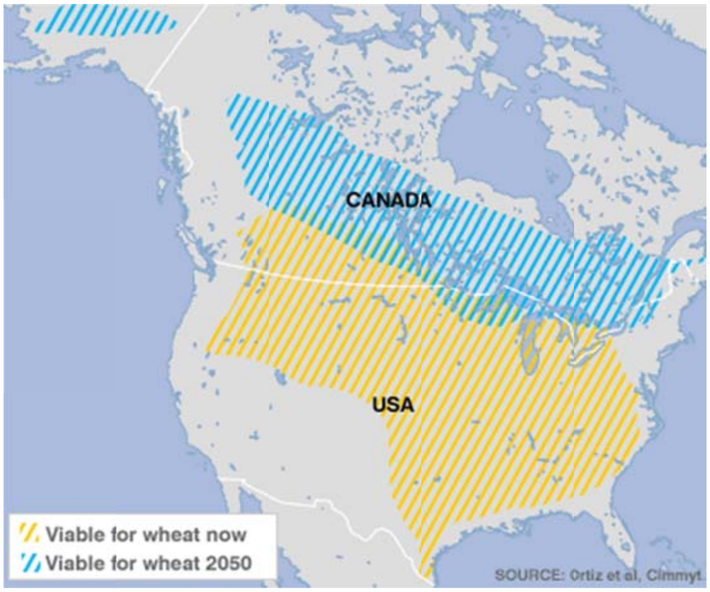
Figure 1

Panel A, as appearing in original study:



Source: Rodomirio Ortiz, Kenneth D. Sayre, Bram Vovaerts, Raj Gupta, G. V. Subbarao, Tomohiro Ban, David Hodson, John M. Dixon, J. Ivan Ortiz-Monasterio, and Matthew Reynolds, “Climate change: Can wheat beat the heat?” *Agriculture, Ecosystems and Environment* 126 (2008): 46-58.

Panel B, as translated by the BBC:



Source: Richard Black, “New crops needed to avoid famines,” BBC News, 3 Dec, 2006. http://news.bbc.co.uk/2/hi/science/nature/6200114.stm

Figure 2: Klippart's "Potential Wheat-Producing Area" in the North America in 1858.

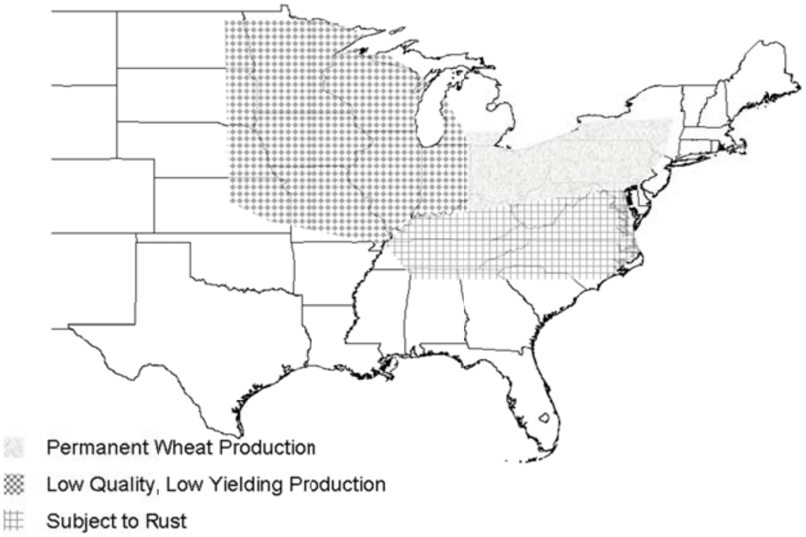
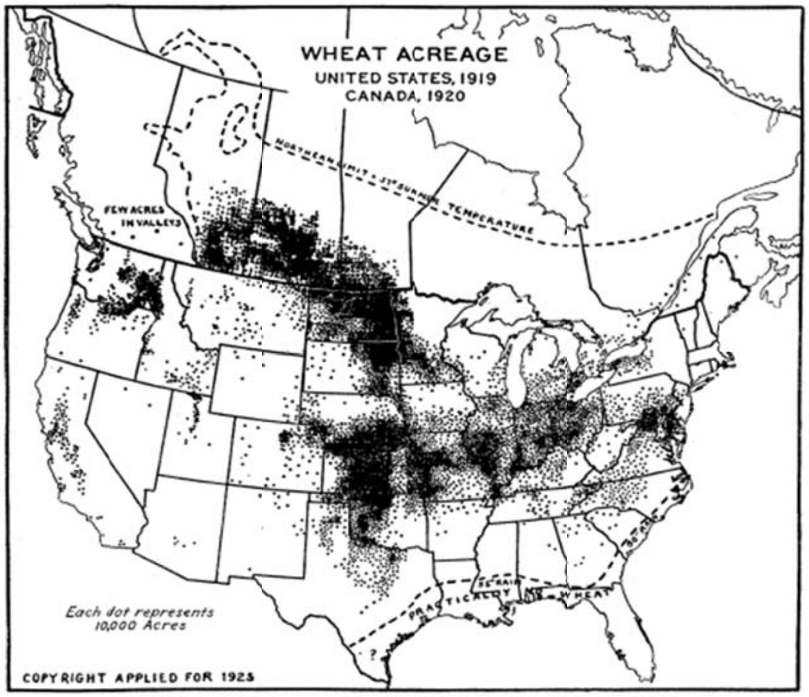


Figure 3: North American Acreage in Wheat in 1919-20.



Source: Oliver E. Baker, "Agricultural Regions of North America. Part VI -The Spring Wheat Region," *Economic Geography*, 4:4 (Oct. 1928), pp. 399-433, esp. p. 402.

Changing location and conditions of production in North America

Between 1839 and 2009, wheat output increased 26 times in the United States and more than 270 times in Canada. In 1839, the geographic center (mean) of North American wheat production was located in eastern Ohio.[12] Cultivation was concentrated in Ohio and New York; relatively little was grown as far west as Illinois. Today (2007) the center of production has moved 1,800 km, into west central South Dakota.[13]

The change in the location entailed large shifts in growing conditions. The six panels of Figure 4 display the main features of the changing geographic distribution of the North American wheat crop across latitude; longitude; annual, January, and July temperature norms; and annual precipitation norms. The series cover the period from 1839 to 2007, utilizing county-level information from U.S. and Canada.[14] The distributions summarized in Figure 4 weight the fixed county-level geo-climatic characteristics by output in each locality at each date.

Figure 4A summarizes the changing longitude of wheat production in North America over roughly 170 years. The median production shifted 21 degrees west (nearly 1800 km) between 1839 and 1929, with little movement thereafter. By 1879, the median was beyond the extreme western boundary of production in 1839. The median latitude of production (Figure 4B) was relatively constant until the 1890s when the northern Plains and the Canadian Prairies began to enter cultivation. In 1929 the median production was at a latitude near the northern fringe of production (the 95 percent line) in 1839. The most northern one-quarter of production (reflected in the 75 percent line) moved 8 degrees of latitude (over 880 km) between 1839 and 1929.

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[12] We start in 1839 because it is first year U.S. Census data become available. It is not the natural starting part of the expansion process. Fifty years early, wheat production in North America was concentrated in Quebec, and the seaboard regions of the Middle and Chesapeake states in the U.S.

[13] We extracted county-level U.S. wheat production data for 1839 to 1909 from Inter-University Consortium for Political and Social Research [ICPSR], *Historical Demographic, Economic, and Social Data, 1790-2000*, ICPSR 2896. The U.S. data for after 1909 come from the *Censuses of Agriculture*, various years. Canadian data are from *Agricultural Census of Canada*, supplemented by sundry provincial sources to fill gaps in the Census data between 1950 and 1976. We linked production to each U.S. county's location based of its 1970 population centroid as reported in U.S. Department of Health and Human Services, *Bureau of Health Professions Resource File*, ICPSR 9075. For Canada, we linked production to a fixed location, often a weather station or seat of government, with each local unit.

[14] The geo-climatic variables reflect average 1941-70 conditions in each county or agricultural district as recorded by U.S. National Oceanic and Atmospheric Administration or the Canadian Atmospheric Environment Service. The U.S. norms are from U.S. Department of Health and Human Services, *Bureau of Health Professions Resource File,* ICPSR 9075. The Canadian weather norms come from Atmospheric Environment Service [Canada] (1972), *Temperature and Precipitation,* 1941-1970, 6 vols., Department of the Environment, Downsview, Ontario. These climate norms largely predate the more recent climate changes associated with the global warming.

These changes in location entailed dramatic changes in the distribution of production across climatic conditions. In 1839 the median production took place in an environment with a (1941-70) norm of nearly 100 cm of precipitation (Figure 4C). In 2007, median production took place on land with less than 50 cm of precipitation; this was a drier environment than virtually any place growing wheat in the U.S. or Canada in 1839. Almost all of the changes in the distribution of production, as measured by annual precipitation, had occurred by 1929. In that year the marginal fringe (the 10 percent line) with 35 cm or less of precipitation produced about one-fifth more wheat than North America's total output in 1839. The range of annual moisture conditions widened substantially, as indicated by the growing spread between the 10 and 90 percent lines. As a quantitative indicator of the extent of the precipitation changes, the driest 10 percent of North American production moved from areas with 7.8 cm of rain in July in 1839 to areas that averaged 0.9 cm in 1889.

The median annual and January temperature norms fell by 3.7 degrees C and 5.9 degrees C respectively between 1839 and 2007 (Figure 4D and Figure 4E). The range of temperature conditions greatly widened, with a pronounced movement into colder domains. The 90-10 differential in annual temperature doubled from 6.3 to 13.1 degrees C over past 170 years. Again, most of the change occurred before the dawn of modern plant sciences. Focusing on annual temperature norms, the coldest 10 percent of production occurred at 8.4 degrees C in 1839 but at 1.6 degrees in 1929. The fall in winter temperature was more extreme (Figure 4E). The coldest 10 percent of production as measured by January temperature occurred where the norm was -5.1 degrees in 1839 but -17.7 degrees in 1929, a fall of 12.6 degrees. In 1929 much more wheat was grown in places where the January temperature norm averaged less than -17 degrees C than was grown in North America in 1839—a date when little wheat was produced in areas with a January temperature norm as low as -7 degrees. The colder production locations have also tended to be drier, although as discussed below, this relationship weakened over time. The production-weighted correlation coefficient between annual temperature and precipitation was 0.70 in 1839, 0.54 in 1929, and 0.51 in 2007. Wheat cultivation spread to a wider range of climatic conditions.

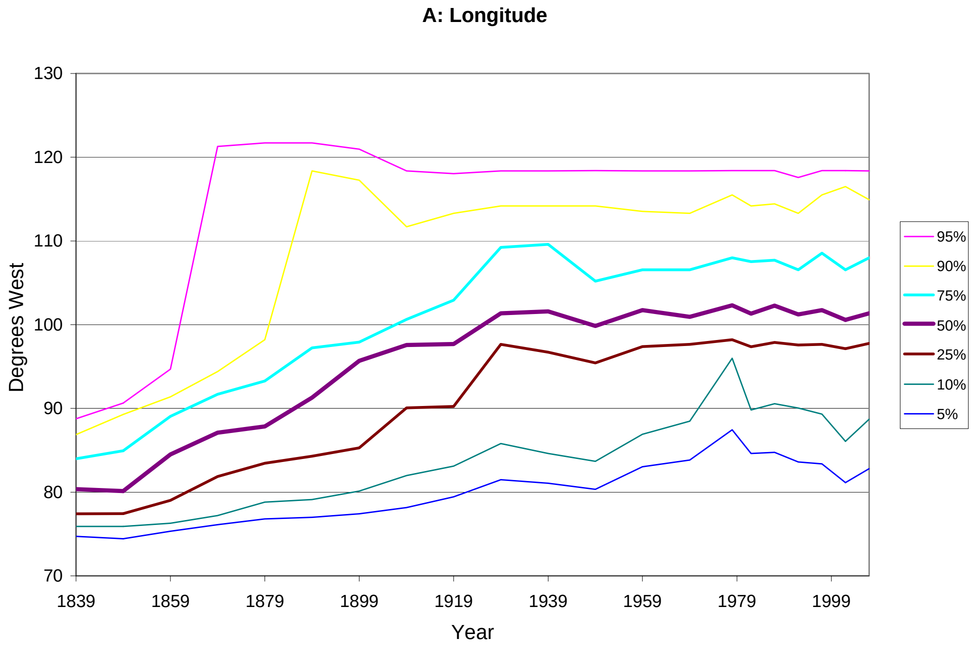
The changes have not been limited to moving into places with colder climates, but the expansion in hot areas has been swamped in our figures by the much greater geographical shift into cold areas. Figure 4F shows that, while the median July temperature norm declined, the July temperature in the area supporting the warmest one-quarter of production increased. In 1839, 5.1 million bushels of wheat were produced in areas with a July temperature norm of 26 degrees C or hotter. By 1929 over 192 million bushels were produced under such conditions.

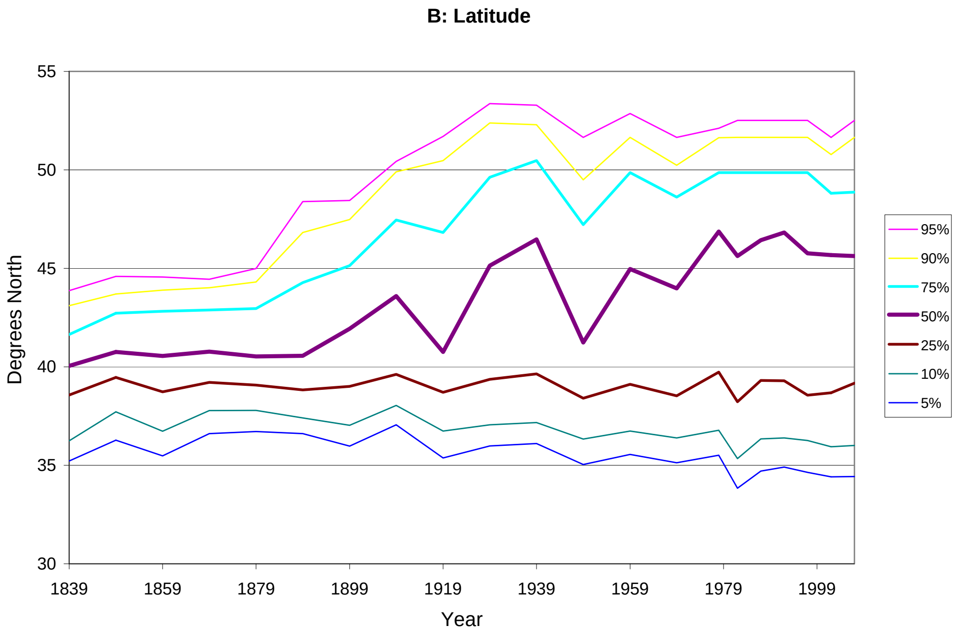
Thus, well before the Green Revolution of the 1960s and 1970s, generations of North American farmers overcame significant climatic challenges to push wheat production into environments once considered too arid, too variable, and too harsh to cultivate. As summary measures, the median annual precipitation norm of the 2007 distribution of North American wheat production was one-half that of the 1839 distribution, that is about 50 fewer cm; the median annual temperature norm was 3.7 degrees C lower.

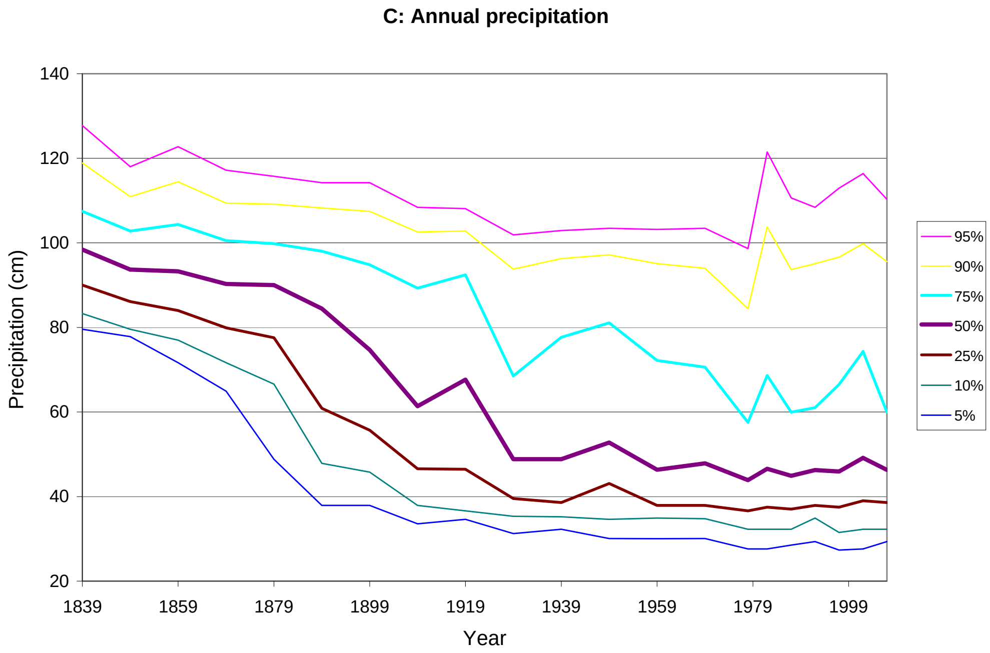
New views of the changing distributions of production conditions

Figure 5 presents an alternative way of viewing these changes by graphing the entire distribution of wheat production for four selected years—1839, 1899, 1929, and 2007. Such figures help distinguish between cases where the entire distribution shifts from those where the changes are concentrated principally in a portion of the distribution. As an example, for longitude, the western shift affects the entire distribution whereas for latitude, the changes occur primarily at the top (more northern portion) of the distribution. (In the longitude and latitude figures, “600000” refers to the 60th degree, and so on.) The distributions displayed in this way also pick up finer-grained changes. As one example, the panel on longitude (Figure 5A) shows the retreat in the western fringe of production (see the area around the 120 degree) longitude between 1899 and 1929 following the collapse of the California wheat industry. As another example, there is a movement in the temperature distribution (Figure 5D) above 12 degrees between 1929 and 2007. But more generally, the panels on annual precipitation and temperature serve to demonstrate how much of the movement to drier and colder domains occurred between 1839 and 1929.

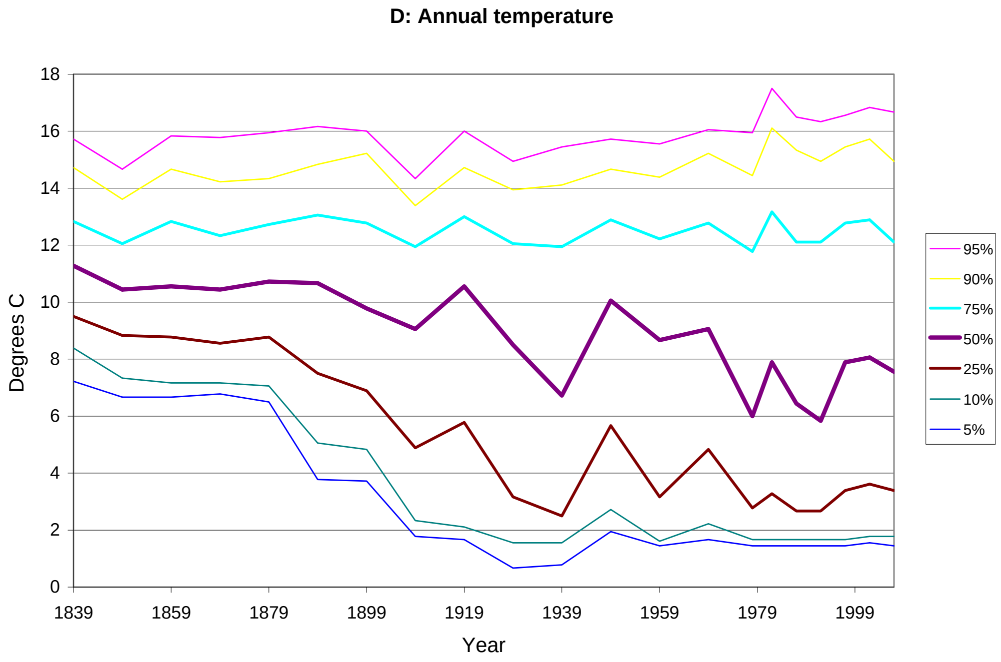
Figure 4: Changing Distribution of North American Wheat Production



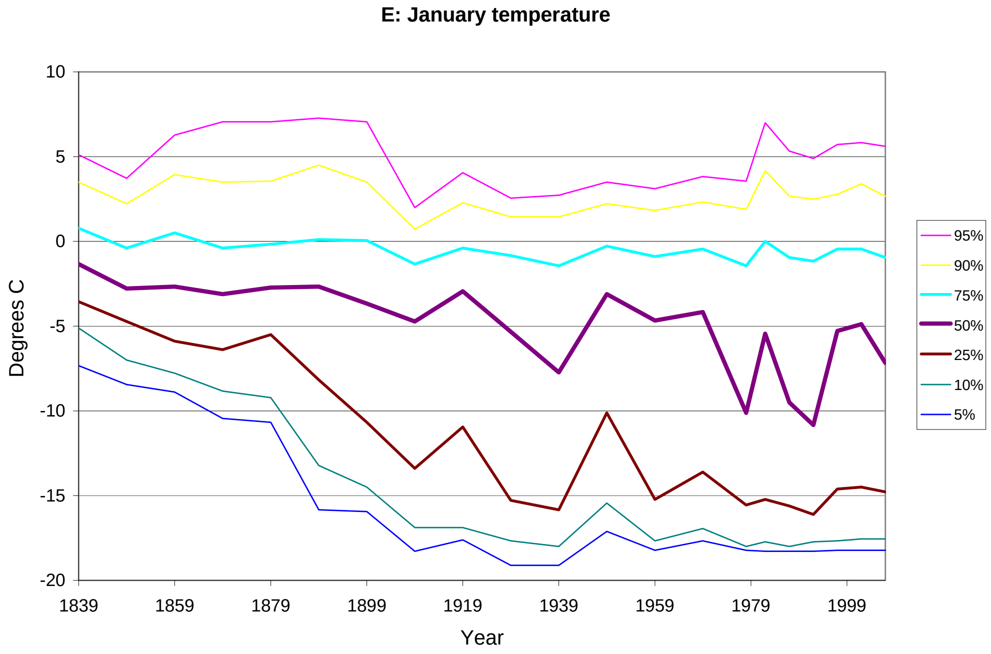




C: Annual precipitation



D: Annual temperature


E: January temperature
10
5
0
-5
-10
-15
-20
Degrees C
1839
1859
1879
1899
1919
1939
1959
1979
1999
Year
95%
90%
75%
50%
25%
10%
5%

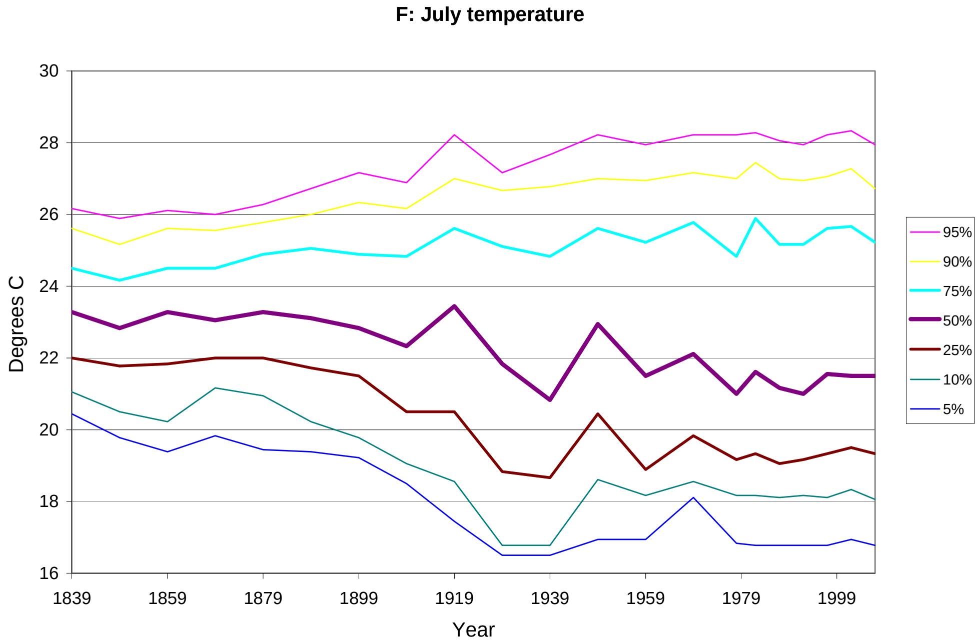
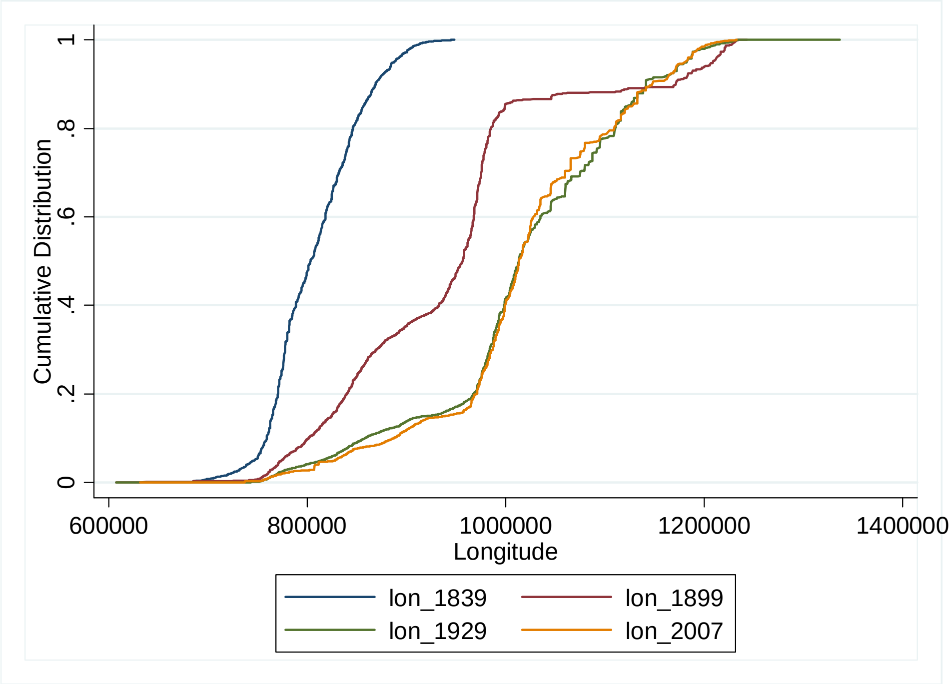
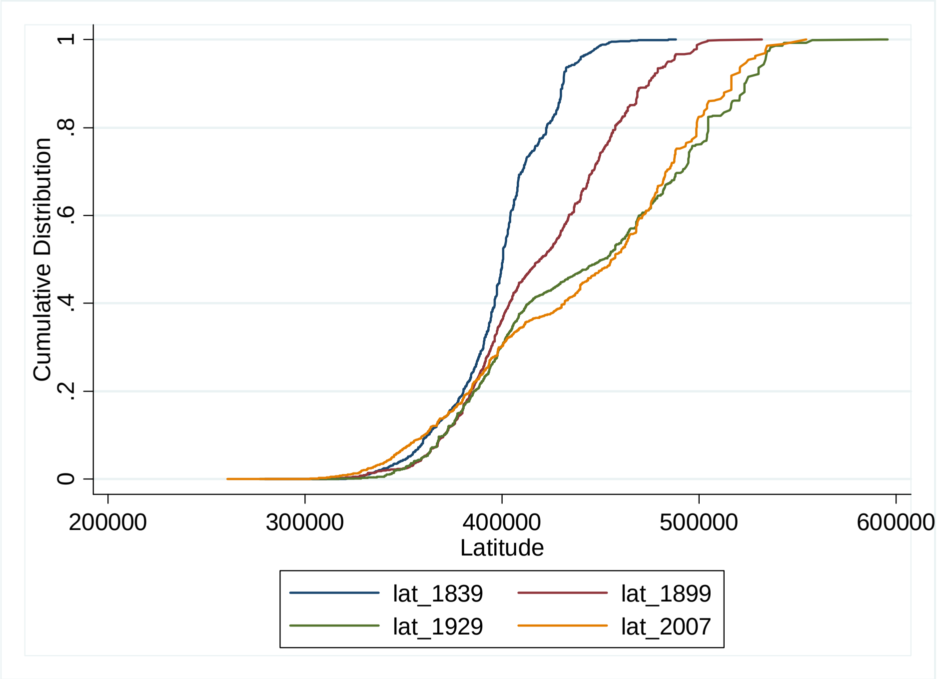

F: July temperature
30
28
26
24
22
20
18
16
Degrees C
1839
1859
1879
1899
1919
1939
1959
1979
1999
Year
95%
90%
75%
50%
25%
10%
5%

Figure 5: Distribution of North American Wheat Production on 1839, 1899, 1929, and 2007

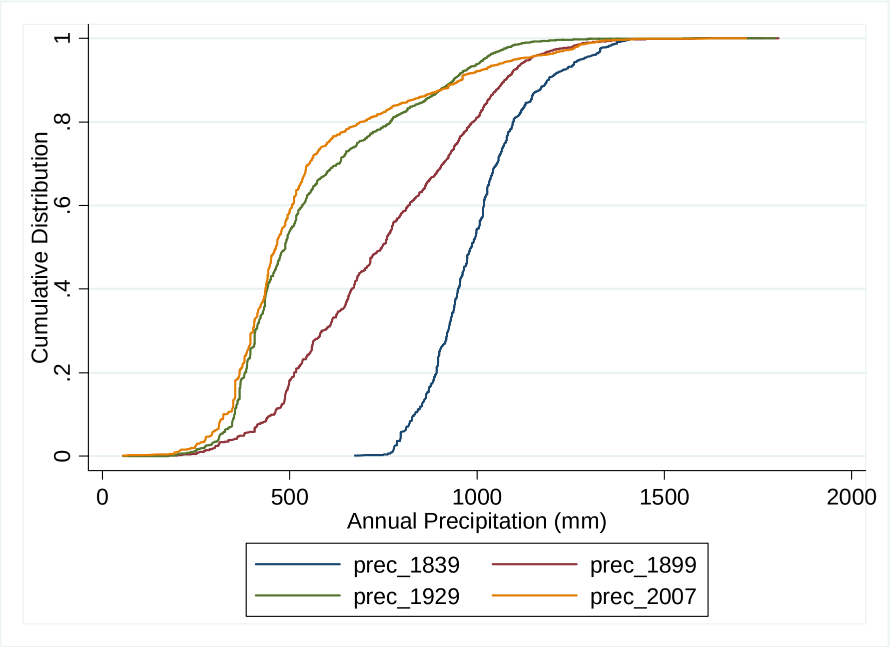
A: Longitude



B: Latitude



C: Annual Precipitation



D. Annual Temperature

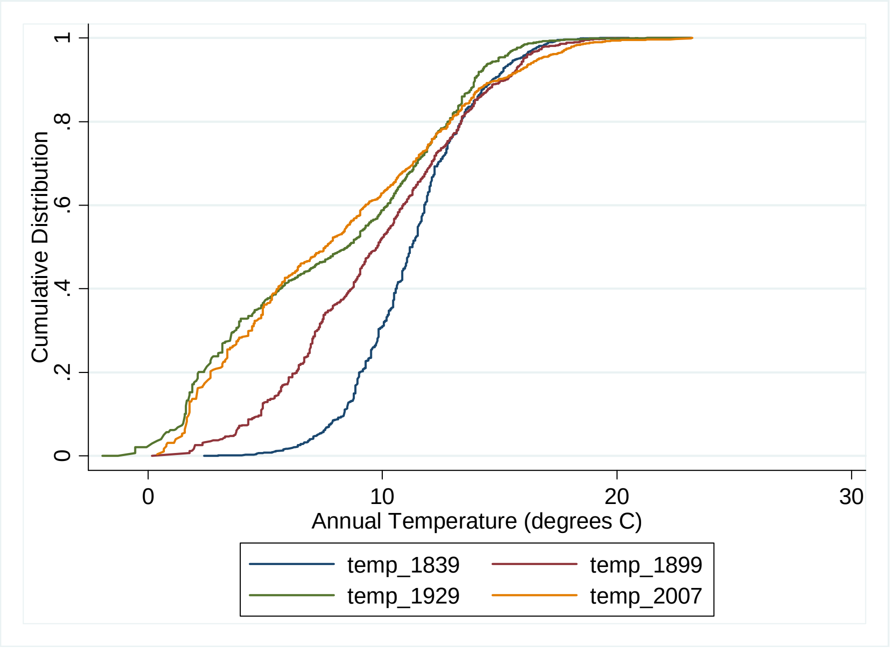
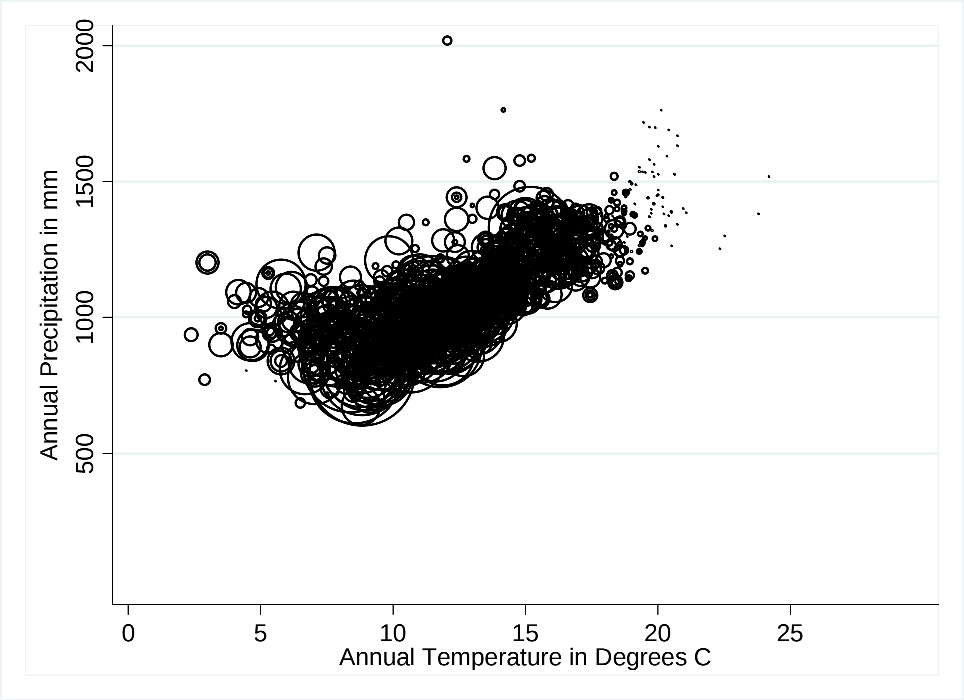
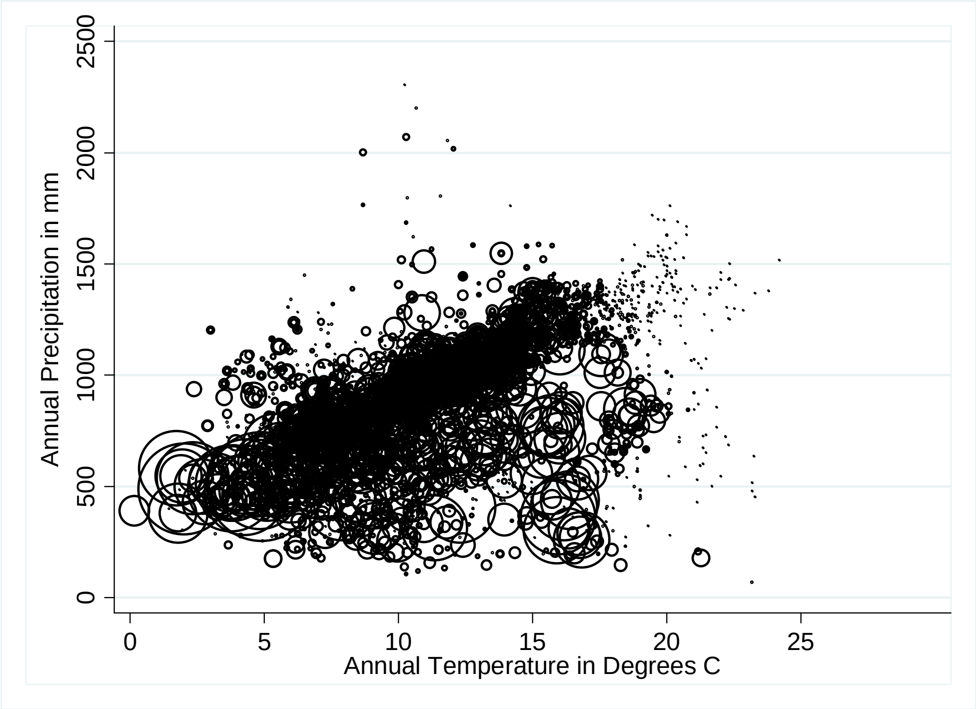


Figure 6: Changing Temperature and Precipitation Correlates

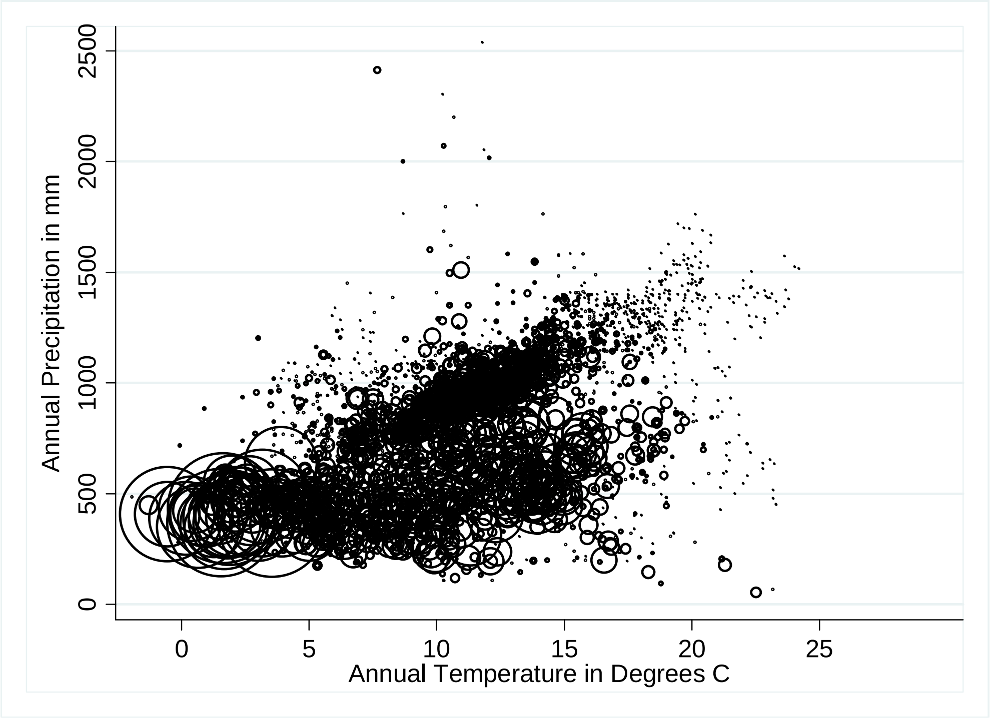
Panel A: 1839



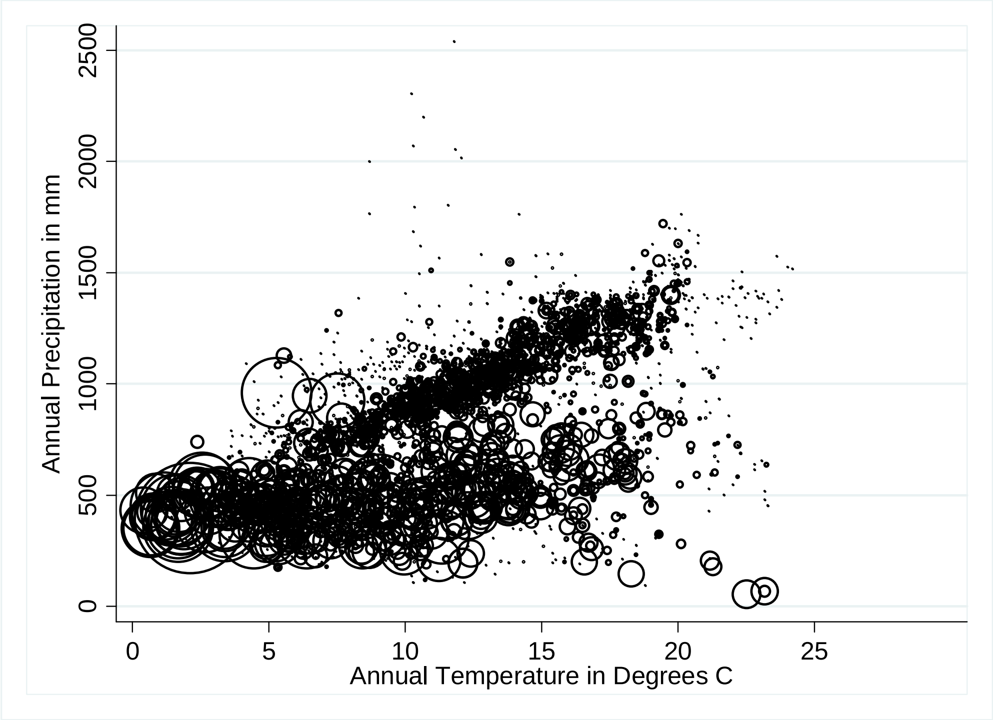
Panel B: 1899



Panel C: 1929



Panel D: 2007



Our county-level North American data set allows us to investigate how correlation between temperature and precipitation norms changed over time. Figure 6 shows the changing correlations between annual precipitation and temperature conditions. Each observation represents a county and the size of the circle is scaled to its relative share in total wheat production. In 1839, there is a strong positive relationship between temperature and precipitation. Producing areas with hotter annual temperature were also wetter; and the relationship was tight. Over time, the relationship weakens. The weighted regression results presented in Table 1 summarize these changes. The relationship between precipitation and temperature does not merely shift down (as indicated by the decline in the constant term), but it also pivots (as indicated by the decline in the slope term). The tightness of the relationship also changes over time as indicated by the movements in the R-squared. Eventually a new cluster of points emerges which is separate from the old cluster and displays a very flat relationship between precipitation and temperature. Almost all of the points in the new cluster were located west of the 100 degree longitude. The changes in the production possibilities at different combinations of temperature and precipitation were made possible by the biological innovations discussed below.

Table 1: Robust Weighted Regression of Annual Precipitation on Annual Temperature

Year	1839	1899	1929	2007
Constant	570.4	470.6	333.4	343.4
(RSE)	(25.4)	(25.8)	(10.2)	(16.1)
Ann_Temp	38.16	28.92	25.02	25.14
(RSE)	(2.09)	(3.16)	(1.33)	(1.84)
R-sq	0.49	0.21	0.30	0.27
N	1248	2753	2769	2095

Notes: county climate observations weighted by wheat production.

Effects of relocation on yield potential

The geographic relocation of wheat in North America tended to push production onto lower-yielding lands. We can conduct a simple accounting exercise to gauge the magnitude of the effect by fixing the yield at each location and considering how the changing distribution of acreage across locations affected aggregate yields. The U.S. Census first reported the acreage data required to derive yields in 1879. 1929 represents a suitable stopping point because the relocation process was largely completed (and the distorting effects of government crop allotment policies were not yet present). In our accounting exercise, we first calculate the mean yield for each county over the 1879 to 1929 period. For each census year, we then multiply this mean yield by the county's share of total wheat acreage and sum. The resulting number indexes show, holding yields fixed the changing geographic distribution of output affected counterfactual yields. Table 2 presents the counterfactual yields as well as actual (North American) yields.[15] As it shows, every decade over this period, wheat production was moving, on average, to lower-yielding lands. The distribution of wheat acreage of 1929 was associated with 12 -13 percent lower yields than that of 1879.

Table 2: Effect of Changing Distribution of Production on Yields

	Reported Yields	Counterfactual Yields	Counterfactual Adjusted Yields*
1879	13.0	14.7	13.4
1889	14.1	14.2	13.0
1899	12.6	13.6	12.4
1909	15.3	13.4	12.3
1919	12.9	13.1	12.1
1929	13.4	12.7	12.0

* See footnote 15.

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[15] U.S. and Canada yields may not be directly comparable because U.S. acreage is reported as acres harvested. The adjusted yields convert to an acreage-planted basis assuming the 1919-1929 average ratio of 0.908. A further complication is that the panel of counties is unbalanced, that is, the sample does not contain every county in all the years. When calculating the average yield for newly formed counties, for example, we have data for the latter part of the sample period but not for the earlier part. The trend in yields at given locations is moderately positive over the 1879 to 1929 period. -- a fixed effect regression run over the county-level U.S. and Canadian data yields an estimate of 0.56 percent increase per annum (st. error 0.014). This means the bias created by the sample runs against our result.

Taking a global perspective

The changes in North American grain-growing conditions in the late-19th and early-20th centuries were part of a worldwide process. The farmers who extended the wheat frontier in Australia, Argentina, Russia and other regions also faced significant environmental challenges. The global shift of wheat cultivation had dramatic effects on median growing conditions, with a movement from maritime areas with temperate climates to drier and colder continental zones with more variable climates. Table 3 uses data on the distribution of world wheat production across different geo-climatic zones to document these changes.[16] In 1926-30 median world production was distributed to lands where the annual temperature averaged 3 degrees C colder and which received 11 fewer cm of precipitation per year than the areas where wheat had been cultivated in 1866-70.

Given expanding production in temperate Europe, the changes in the conditions facing farmers near the frontier were significantly greater than the changes in the average conditions.[17] The 1926-30 land base was also associated with lower average yields per planted acre (15.3 bushels). Had the acreage been distributed as it was in 1866-70, yields would have averaged 20.7 bushels, 35 percent higher. As the researchers at Stanford's Food Research Institute noted, there was a tendency

> for yields of wheat to decline from east and west toward the interior regions of each of the principal land masses, North America and Eurasia. The central regions of such large continents not only suffer from generally light precipitation, but are also characterized by extreme variations

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[16] The construction of the data involves aggregating regional FRI statistics on acreages, yields, and climates. M. K. Bennett and Helen C. Farnsworth, "World Wheat Acreage, Yields, and Climates," *Wheat Studies* 13, no. 6 (March 1937): 265-308. The FRI series do make adjustments for the U.S. and Russia that create differences from standard series. The FRI data exclude "large wheat-producing areas in China and southwestern Asia, and also numerous insignificant producing areas." We are working to incorporate data on China.

The climate data were constructed from data in "World Wheat Acreage," appendix data, pp. 303-308. This presents a highly detailed survey of the geographic distribution of wheat acreage, yields, and climates covering 223 subunits. For each subunit, the FRI reports the acreage (planted), yields, and average precipitation and temperature that were typical during the 1920-34 period. We formed national aggregates, reflecting average conditions prevailing in the wheat-producing areas, that can be combined by using weights derived from the production data investigated above to derive series showing the changing conditions under which wheat was grown.

[17] The fall in the average temperature was also dampened by the movement of production into hotter regions of Australia, the United States, etc. The above estimates understate the change in the conditions of wheat production because they rely on country level data—as we have shown above, in North America within countries wheat production moved to harsher climates.

> in precipitation and temperature.... These climatic characteristics are generally unfavorable for wheat yields.[18]

Clearly, global wheat cultivation was shifting to poorer lands, making the actual growth of world yields over this period all the more impressive. Actual world yields rose 17 percent between 1886-90 and 1926-30 in spite of a geographic redistribution of production that should have, all else equal, led to a 12 percent decline.

Table 3: Changing Climatic Conditions and Yields of Global Wheat Production

	Annual Temperature (Degrees C)	Pre-harvest Temperature (Degrees C)	Annual Precipitation (mm)	Yield in Bushels Per Acre
1866-70	14.3	20.1	734	20.7
1886-90	12.7	18.6	683	17.2
1910-14	11.7	18.3	641	15.7
1926-30	11.2	18.0	624	15.3

Note: The series were derived from fixed national climate and yield values reflecting typical 1920-34 conditions and changing national shares in global wheat production. The 1866-70 data were derived from splicing the 1866-99 series for the 17 countries to the 1885-1930 series calculated for the full FRI sample.

How did these changes happen?

Agricultural production is location specific, at the mercy of conditions that differed across regions and even across neighboring farms. Settlement was intrinsically a biological process that required farmers to harmonize production practices with specific local soil and climatic conditions. The new lands often required new varieties and cultural techniques for wheat-growing to thrive. This lesson is powerfully illustrated by the repeated early failures experienced by settlers who brought seeds and practices inappropriate to their new and strange environments. Success often involved selecting an area to settle that had an environment similar to that back "home." One prominent example is the Mennonites who moved from the Russian

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[18] Bennett and Farnsworth, "World Wheat," p. 283.

steppes to Great Plains of North America in the late-19th century. Among their cargo was Turkey wheat, a hard red winter wheat that became a mainstay in the southern wheat belt. Success for those farmers already in place often involved searching for suitable seed from around the world. Sometimes this occurred through happenstance as in the case of the 1842 discovery by David and Jane Fife of a hardy hard red spring wheat amongst packet of winter wheat seed sent from Scotland (the seed was originally from Eastern Europe). This wheat, named after Fife, made possible the expansion of grain cultivation across the northern plains and Canadian prairies. Increasingly, the search for suitable germplasm took on a systematic global nature. At the turn of the 20th century, Mark Alfred Carleton of the U.S. Department of Agriculture scoured the Russia Empire seeking wheats that thrived in harsh environments. He introduced scores of new varieties, including durum wheats, to the Great Plains.

Many varietal innovations were the result of government investments in breeding. In 1886 the Canadian Parliament created a federal experiment station system. Its most acclaimed breeder, William Saunders, commenced a systematic program of hybridizing high-quality cultivars with early-maturing wheats introduced from around the world. In 1903 his son, Charles Saunders, took over the work at the Dominion Experimental Farm, near Ottawa. The most valuable result of their combined research efforts was Marquis, a cross between Red Fife and Red Calcutta, a very early wheat from India. Released in 1909, Marquis was an immediate success and accounted for the vast majority of wheat acreage in Canada and the northern U.S. by 1920. In Australia government researchers made innovations that were more akin to those needed to confront global warming—the most important innovation was William Farrer's breeding of Federation, which helped extend wheat into hot and arid regions previously too hostile for cultivation. There are similar stories of government-supported researchers helping expand wheat's geographical domain in South America, Africa, Europe, and Asia.[19]

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[19] Olmstead and Rhode, "Biological Globalization," pp. 115-40

Concluding remarks about crop predictions

Since the time of Malthus, there have been dire predictions about future of the world's food supplies. The repeated failures of such projections have led many observers to dismiss the entire "pessimistic" enterprise out-of-hand. But it is important to recall the example of Sir William Crookes whose prophecies of mass starvation in his presidential address to the British Association for the Advancement of Science received wide currency in the closing years of the 19th century. Crookes worried that the settlement and globalization process discussed above was coming to an end, the world is running out of new wheat lands, and the food supply would soon fail to keep pace with population. [20]

Crookes' predictions, though proved wrong, were not without consequences. For Crookes himself argued there was a way out, namely to learn to fix atmospheric nitrogen to create fertilizers to raise yields on existing soils.[21] Crookes' powerful statement of the problem and his proposed solution prompted the chemist Fritz Haber to initiate a search for such a new technology. Haber began experimenting with ammonia in 1904 and after a hit-and-miss start gained the support of the German chemical giant Badische Anilin-- und Soda--Fabrik (BASF) in 1908. In July 1909 Haber sent a letter to the BASF directors describing his recent breakthrough in synthesizing ammonia. Led by Carl Bosch, who headed BASF's nitrogen fixation research, the company overcame numerous technical obstacles to translate Haber's experimental procedures into a large-scale commercial operation. BASF's first ammonia fertilizer plant went on line on 13 September 1913. Subsequent improvements in the production process dramatically increased the supply of nitrogen while lowering it price. Vaclav Smil has elevated Fritz Haber and Carl Bosch's nitrogen synthesis processes to high prominence. Smil, for example, claims that "without this synthesis about 2/5 of the world's population would not be around."[22] Haber (with Borsh's aid) rendered Crookes' prophecies wrong not by adopting a dismissively optimistic attitude, but rather by taking Crookes' challenges seriously and searching for a creative response.

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[20] *Manchester Guardian*, 8 Sept. 1898, pp. 4, 10.

[21] Thomas Parke Hughes, "Technological Momentum in History: Hydrogenation in Germany 1898-1933," *Past and Present* 44 (Aug. 1969): 106-32.

[22] Vaclav Smil, *Enriching the Earth Fritz Haber, Carl Bosch, and the Transformation of World Food Production*, Cambridge, MA: MIT Press, 2004, p. xv.