Adjusting to Climatic Variation:
Historical Perspectives from North American Agricultural Development

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Abstract: Providing greater historical perspective would enlighten current discussions about future human responses to climatic variation. During the nineteenth and twentieth centuries, new biological technologies allowed North American farmers to push cropping into environments previously thought too arid, too variable, and too harsh to cultivate. We document these changes for three major staple crops noting that the climatic challenges that previous generations of farmers overcame often rivaled the climatic changes predicted for the next hundred years in North America.

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According to the U.N. Intergovernmental Panel on Climate Change, the earth's temperature has been rising by 0.2 degrees F (0.13 degrees C) every decade for the past fifty years.[1] Many of the leading climate models project that by the end of the 21st century temperatures on the North American continent will be 4-6 degrees F (2-3 degrees C) higher at its coasts and 9 degrees F (5 degrees C) higher at the more northern latitudes.[2] Sea levels may rise between 0.5 and 2 feet. Such changes will have important impacts on economic activity including agricultural production. Researchers at the International Maize and Wheat Improvement Center anticipate North America wheat farmers will have to cease production at the southern end of the grain belt but may be able extend cultivation up another 600-700 miles from the current northern limit of production.[3] Uncertainty and controversy abound and futuristic projections of how global warming will require huge shifts in the location of production have gained wide circulation. Figure 1 offers one informed view of what is in store for wheat producers—wheat production will shift northward into Alaska and the overall territory suitable for production will shrink considerably. Only a sliver of the current wheat-growing domain in North America will remain viable wheat land. It is not clear how such projections account for future technological changes.

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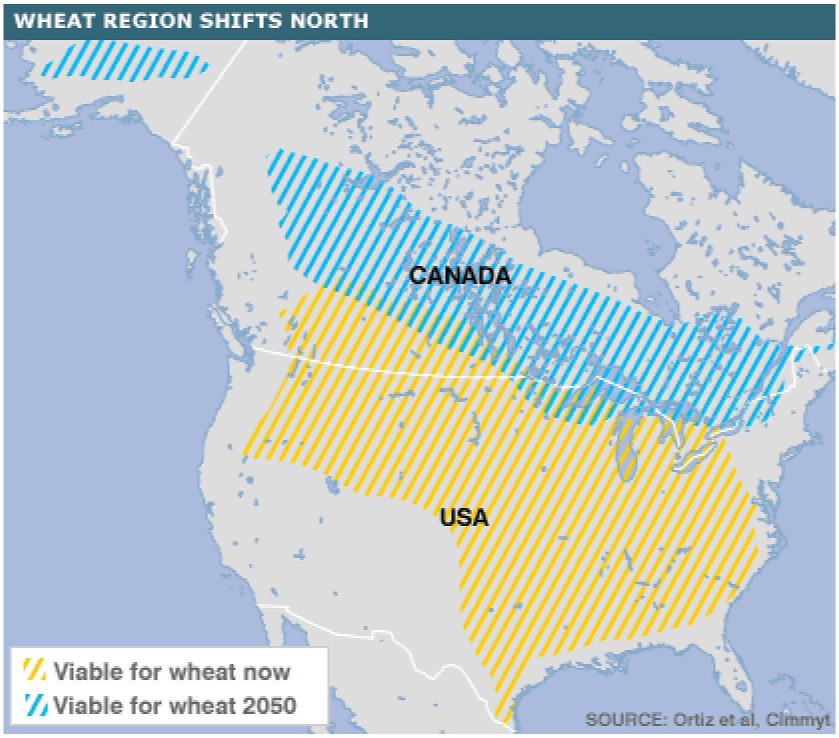
[1] David Fahrenthold, "Climate Change Brings Risk of More Extinctions," *Washington Post*, Sept. 17, 2007; p. A07; Intergovernmental Panel on Climate Change, "Summary for Policymakers," in S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H. L. Miller, (eds,) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, (New York: Cambridge University Press, 2007) ,http://www.ipcc.ch/pdf/assessment-report/ar4/wg1/ar4-wg1-spm.pdf, p. 5

[2] C.B. Field , L.D. Mortsch,, M. Brklacich, D.L. Forbes, P. Kovacs, J.A. Patz, S.W. Running and M.J. Scott, "North America," Ch. 14 in M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, (Cambridge , UK, Cambridge University Press, 2007), entire article is pp. 617-652; cite is to p. 627

[3] Rick Weiss, "Facing a Threat to Farming and Food Supply," *Washington Post*, Nov. 19, 2007, p. A06. The research quoted in the article appears in 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. See Appendix 3 for the North American map reported in this study.

Figure 1:



Source: http://news.bbc.co.uk/2/hi/science/nature/6200114.stm which notes "Map is simplified because existing boundaries are highly complex."

This paper seeks to provide long-run perspective for understanding future adjustments to variation in climatic conditions. Drawing on the record from the past two centuries, we analyze how American and Canadian farmers learned to produce in unfamiliar and challenging environments. 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, locations with significantly harsher, drier, and more variable environments. These changes for the most part occurred before an understanding of plant genetics when agronomy was still in the dark ages. 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 past predictions obsolete.

Agricultural production is location specific, at the mercy of conditions that differed across regions and even neighboring farms. Settlement was intrinsically a biological process that required farmers to harmonize production practices with specific local soil and climatic conditions. Learning did not end when the first settlers gained an agricultural foothold because, as areas matured, farmers generally switched to more intensive production patterns requiring new rounds of experimentation.

The movement of production into more arid regions with more variable climates was one of the hallmarks of American agricultural development. Biological innovation was a necessary condition for this expansion. Some of America's most distinguished historians, including Fredrick Jackson Turner, Walter Prescott Webb, and their many disciples, explored the broader causes and consequences of the westward movement of agriculture. We believe that our quantitative analysis provides a better perspective on the magnitude of the challenges that farmers confronted and offers a hint as to the flexibility of farmers to respond to future challenges. In this paper we analyze the changing location and climatic conditions faced by the producers of America's three great nineteenth century staples—wheat, corn, and cotton. Our analysis of the changing challenges faced by wheat producers in other countries suggests that American farmers were not unique in their ability to adapt production technologies to meet harsher, drier and more variable climates.[4]

WHEAT

In the mid-nineteenth century John Klippart, of the Ohio State Board of Agriculture, was arguably the most informed individual in the United States 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. 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

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[4] This paper draws on and extends material from Alan L. Olmstead and Paul W. Rhode, *Creating Abundance: Biological Innovation and American Agricultural Development* (New York: Cambridge Univ. Press, 2008).

exhausted and without considerable investment in fertilizer, production would soon decline in other states. 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.[5]

Figure 2: The “Potential Wheat-Producing Area” in the United States in 1858

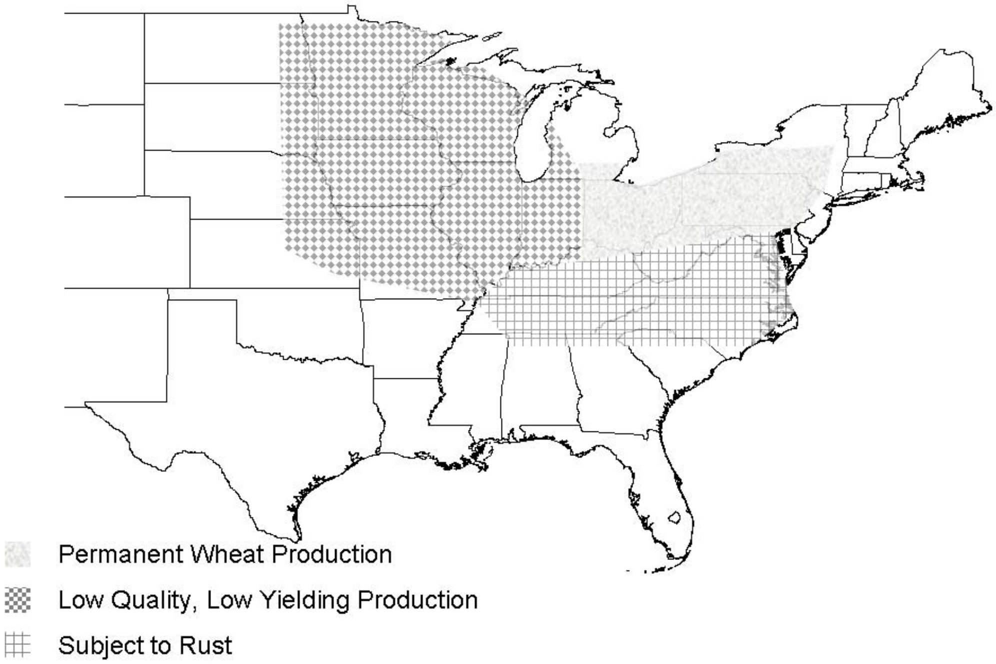

Figure 2 offers a map of Klippart’s vision of the potential long-term wheat-producing area of the United States. Klippart was so far off the mark because he failed to anticipate the wholesale changes in the genetic makeup of the wheat varieties that would soon become available to North American farmers.[6]

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[5] 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. Because of a perceived deterioration in productivity, Klippart argued that “Canada may be left out of the wheat region.” p. 323.

[6] John H. Klippart, *The Wheat Plant: Its Origin, Culture, Growth, Development, Composition, Varieties, Diseases, Etc., Etc*. (New York: A.O. Moore & Company, 1860). Figure 2 offers a crude outline of wheat potential wheat lands that vastly overstates the actual amount of land suitable for the crop because large

Over the 1839-1929 period, U.S. wheat production increased nearly ten times, rising from roughly 85 million to 801 million bushels.[1] The rapid growth in output was crucially dependent on the western expansion of cultivation. These geographic shifts are illustrated in Table 1, which shows the changing geographic center of production of U.S. wheat output from 1839 to 1929.[7] In 1839, the center was located near Wheeling, (West) Virginia. Cultivation was concentrated in Ohio and upstate New York; relatively little was grown as far west as Illinois. By 1929, the center of U.S. production had moved almost one thousand miles west to the Iowa/Nebraska borderlands.

Table 1: Geographic Center of U.S. Wheat Production, 1839-1929

	North Latitude			West Longitude						
	deg	min	sec	deg	min	sec	Miles of Movement			
Mean Location										
1839	39	43	2	80	56	35	1839	-	1849	69
1849	40	16	30	82	1	45	1849	-	1859	217
1859	39	56	40	86	7	24	1859	-	1869	152
1869	40	39	4	88	50	55	1869	-	1879	94
1879	40	33	34	90	39	12	1879	-	1889	148
1889	41	2	50	93	24	59	1889	-	1899	90
1899	41	40	47	94	56	45	1899	-	1909	77
1909	42	24	39	96	5	44	1909	-	1919	125
1919	40	36	20	95	54	5	1919	-	1929	186
1929	41	28	55	99	17	10	Total 1839-1929			967

Source: 1839-1919 calculated using county-level production data from Inter-university Consortium for Political and Social Research, *Historical Demographic, Economic, and Social Data, 1790-2000*, ICPSR 2896 linked to county centroids from U.S. Dept. of Health and Human Services, Health Resources and Services Administration, Bureau *of Health Professions Resource File*. ICPSR 9075; 1929 uses data from the *1930 Census of Agriculture.*

But even more impressive than these changes in geographic center of wheat production were the shifts in the ranges of growing conditions. According to Mark

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areas were too hilly, too wet, or otherwise unsuitable for production. Largely for this reason, between 1839 and 1959, one-fourth of New York's counties accounted for almost all the state's production. Henry Adolf Knopf, "Changes in Wheat Production in the United States, 1607-1960," PhD Dissertation, Cornell University, 1967 p. 169.

For an early twentieth century view of the land suitable for wheat, see J. F. Unstead, "The Climatic Limits of Wheat Cultivation, with Special Reference to North America" *Geographical Journal*, Vol. 39, No. 4 (Apr., 1912), pp. 347-366 and Vol. 39, No. 5 (May, 1912), pp. 421-441,

[7] We calculated the center from Census county-level production data and the location of the county's population centroid. The data include only U.S. production. As a result, the changes do not capture the spread of grain cultivation onto the Canadian prairies, which is displayed in the map in Appendix 2.

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."[8] The nine panels of Figure 3 display the main features of the changing geographic distribution of the U.S. wheat crop across latitudes, longitudes, elevation, annual mean temperature and precipitation, January mean temperature and precipitation, and July mean temperature and precipitation. The series cover the period from 1839 to 2002 and combine county-level production data from the Census of Agriculture with fixed characteristics for each county.[9] For example, the climatic variables reflect average conditions in each county recorded over the 1941-70 period by the National Oceanic and Atmospheric Administration.[10] These variables capture neither year-to-year changes in the weather nor secular climate changes such as the warming trend noted in the introduction.

The panel showing the distribution of wheat production by longitude indicates a steady westward shift in the median location to 1929. The increases in the most westward quantiles (the 99, 95, and 90 percent lines) in the 1850s, 1860s, and 1870s capture the rapid expansion of grain cultivation on the U.S. Pacific coast. Turning to the panel displaying the changing distribution across latitudes, one sees that the median is relatively constant, but the most northern deciles (the 90 percent line) rose by just under 5 degrees between 1839 and 1929. This equals about a 350-mile shift north.

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

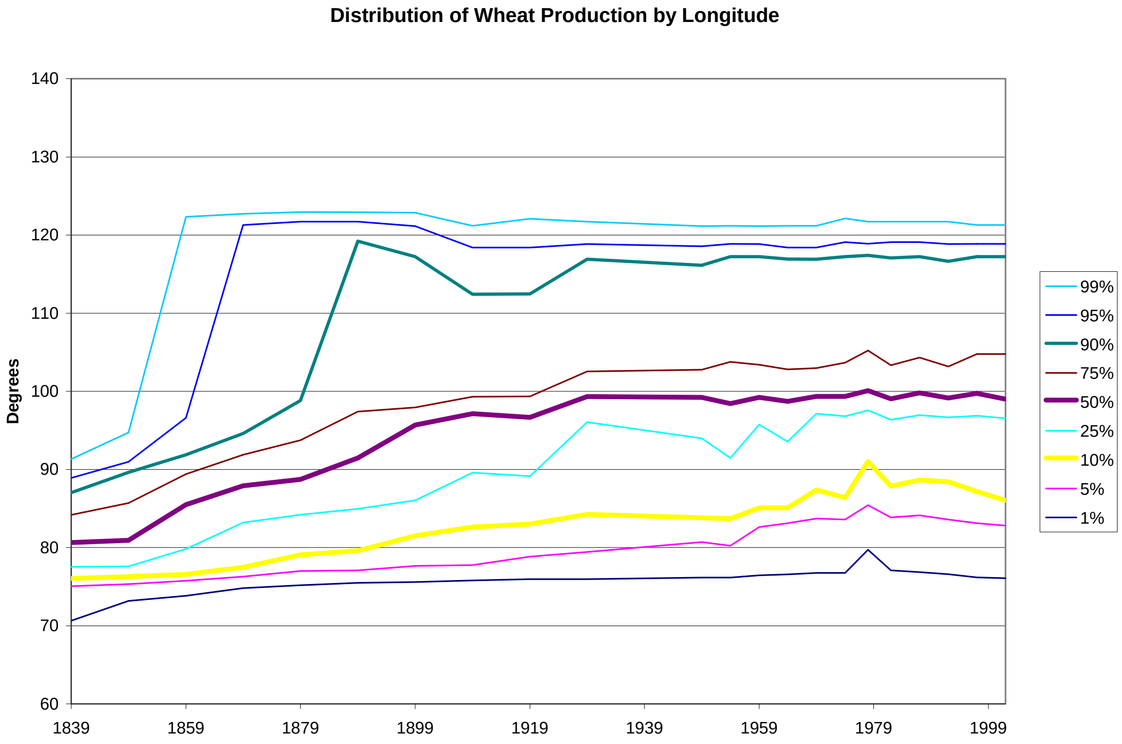
[9] Inter-university Consortium for Political and Social Research, *Historical Demographic, Economic, and Social Data, 1790-2000*, ICPSR 2896 linked to county characteristics from U.S. Dept. of Health and Human Services, Health Resources and Services Administration, Bureau *of Health Professions Resource File*. ICPSR 9075. We owe a large debt to Lee Craig, Michael Haines, and Thomas Weiss for making available machine-readable data for 1839 to 1909. Lee A. Craig, Michael R. Haines, and Thomas Weiss. "Development, Health, Nutrition, and Mortality: the Case of the 'Antebellum Puzzle' in the United States." NBER Working Paper Series on Historical Factors in Long Run Growth, Historical paper # 130, Cambridge, MA, 2000.The data for the period 1839-1909 come from their contributions to ICPSR 2896. The information for 1949 to 2002 comes from machine-readable files from the Census of Agriculture compiled and made readily accessible by Michael Haines. We have entered the data for making the bridge in 1919 and 1929. We are continuing to assemble data for other crops and farm activities from the U.S. Bureau of the Census. *Fifteenth Census of the United States: 1930. Agriculture.* Vol. II*, Reports by States, With Statistics for Counties and a Summary for the United States*. Pt. 1, *The Northern States*, Pt. 2, *The Southern States*, Pt. 3, *The Western States*. Washington, D.C.: GPO, 1932.

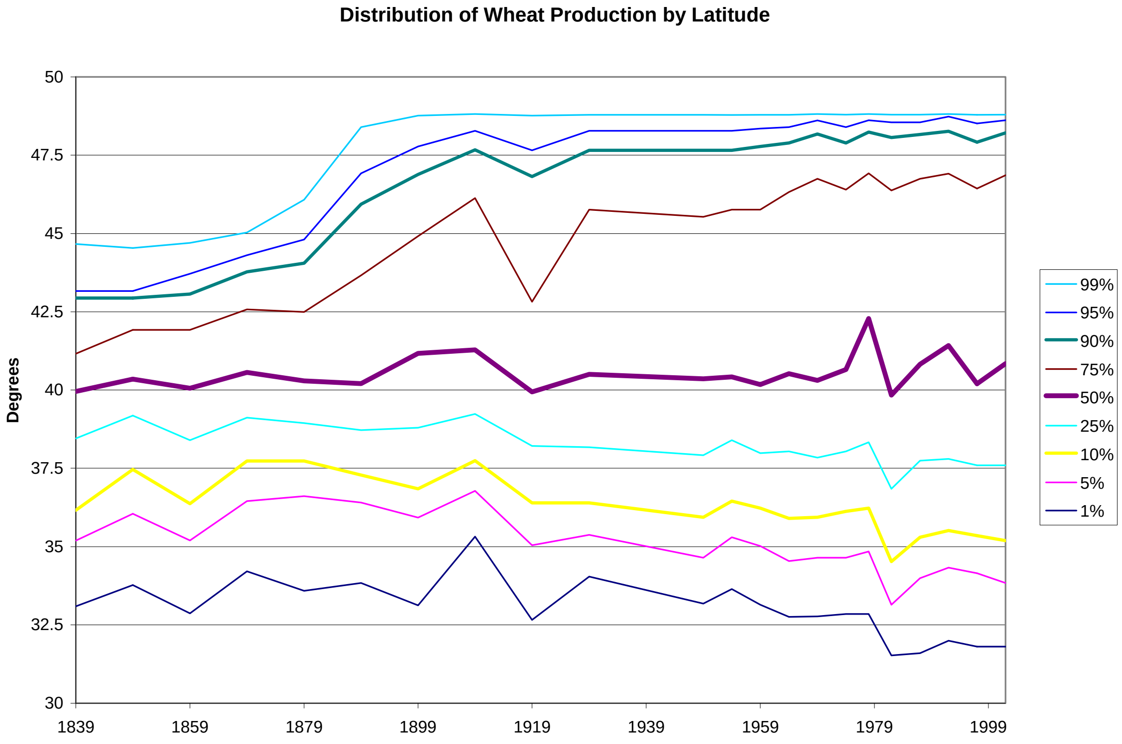
[10] ICSPR-No, 9075 Codebook, p. 96. The available series include mean temperature (Jan., July, Annual); mean precipitation (Jan., July, Annual). "Counties with more than one weather station include data for the station closest to the county's population center(s). For those counties not having a weather station, the U. S. Weather Bureau's climate regions were used to extrapolate data from other similar climatic areas."

Dramatic changes occurred in the distribution of production by annual precipitation. In 1929, median production took place in a drier environment than virtually anything recorded in 1839 or 1849. It is important to note that because of the nearly ten fold increase in wheat production between 1839 and 1929 the quantity of output captured in either the top and bottom 10 percent deciles of Table 1 was about equal to the entire output in 1839. Thus in 1929 the marginal fringe with less than 15 inches of rain produced as much wheat as was grown in the entire United States in 1839. At that time little or no wheat was produced in areas with less than 30 inches of rain. The range of annual moisture conditions also expanded substantially. The story with respect to the distribution of January precipitation is similar. The median environment where wheat was produced in 1929 was far drier than where the driest one percent production occurred 1839 or 1849. The evidence on July precipitation also shows a significant widening of the range of growing conditions driven in part by the movement of production into California where it seldom rained in the summer months.

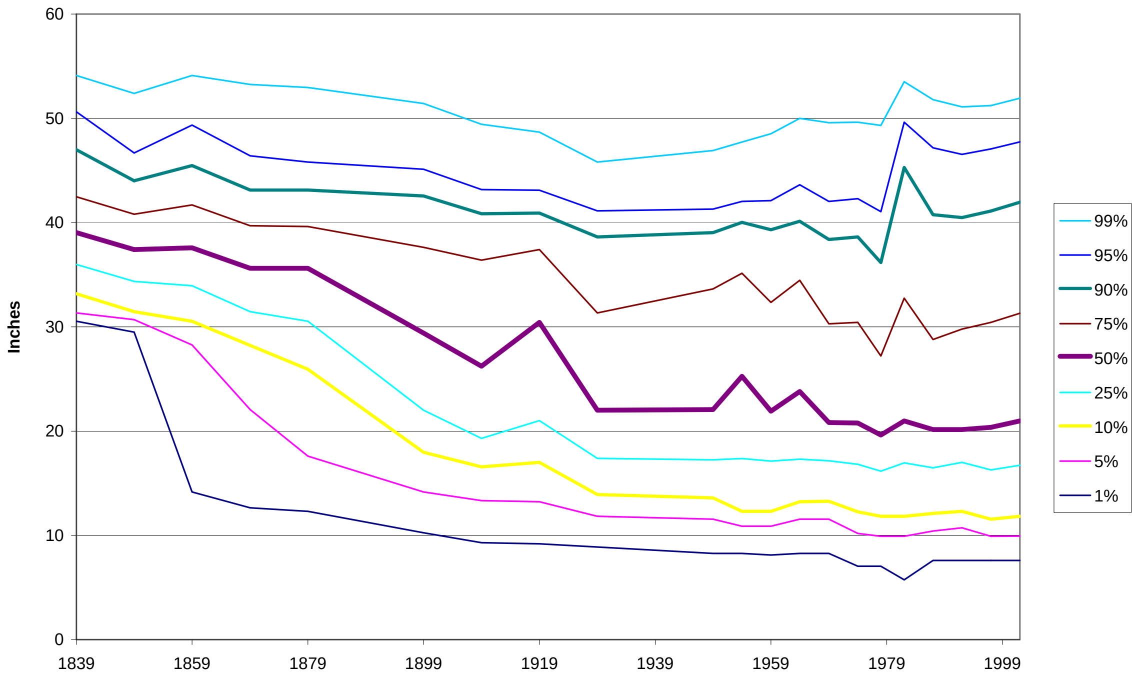
The changes in the median annual and January temperatures were small. But the range of temperature conditions greatly widened, especially in the colder domain. Focusing on annual temperature, the coldest deciles of production (the 10 percent line) occurred at 47.8 degrees F. in 1839 but at 42.8 degrees in 1929, a change of 4 degrees. Turning to January temperature, the coldest deciles of production occurred at 23.6 degrees F. in 1839 but at 8.3 degrees in 1929, a fall of 15 degrees. In 1929 more wheat was grown in places where the January temperature was less than 10 degrees than was grown in the entire nation in 1839—a date when almost no wheat was produced in areas with a January temperature of 20 degrees. The changes have not been limited to moving into places with colder winters. There has also been a small increase in median July temperatures and larger increases at the higher quantiles. Overall, the 90-10 range doubled. Between 1839 and 1929 the median elevation of production increased by about 900 feet and the upper decile (the 90 percent line) rose by almost 2500 feet. In no period did the areas currently threaten by rising sea levels produce more than a trivial fraction of U.S. wheat.

Figure 3: Distribution of U.S. Wheat Production, 1839-2002

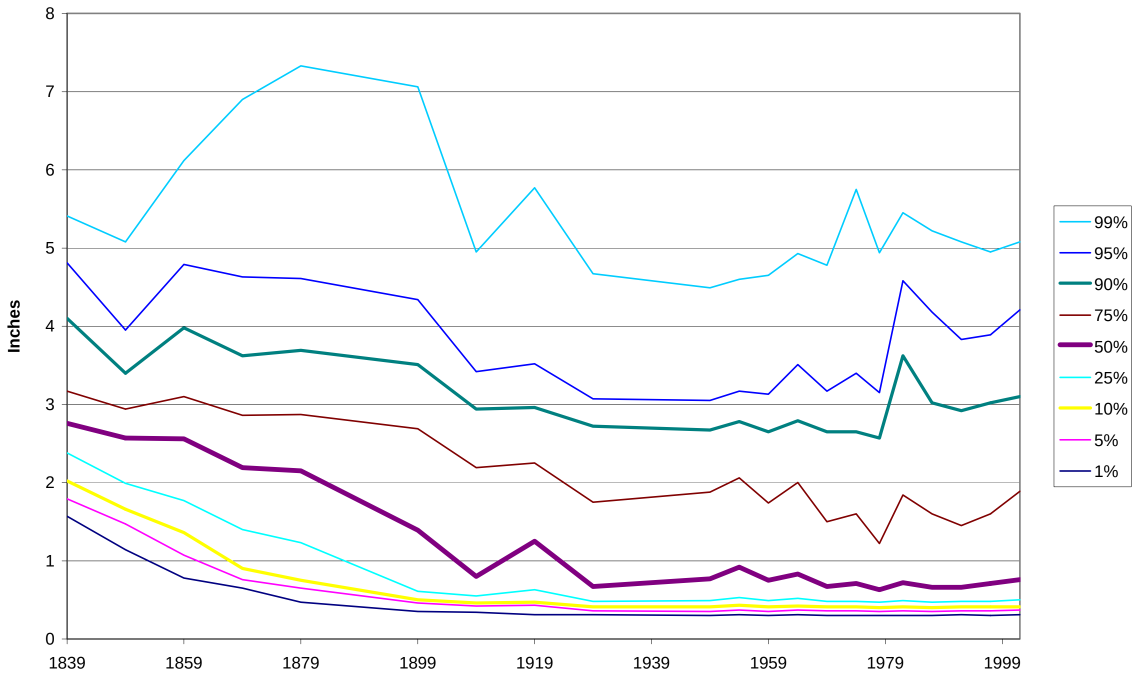




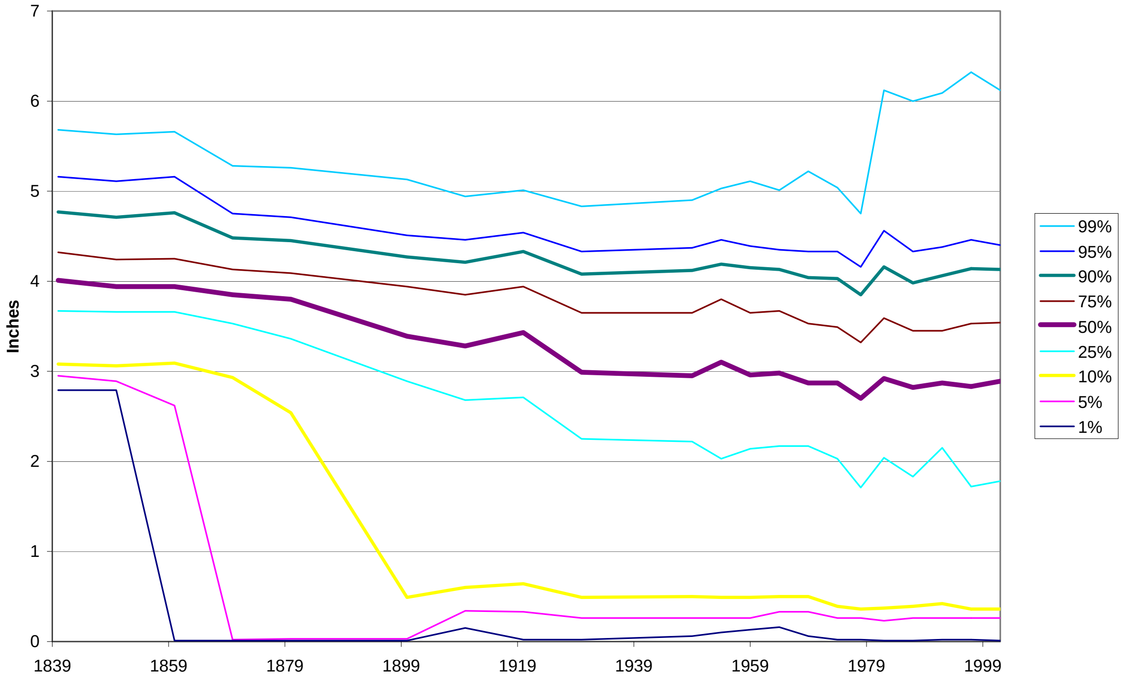
Distribution of Wheat Production by Annual Precipitation



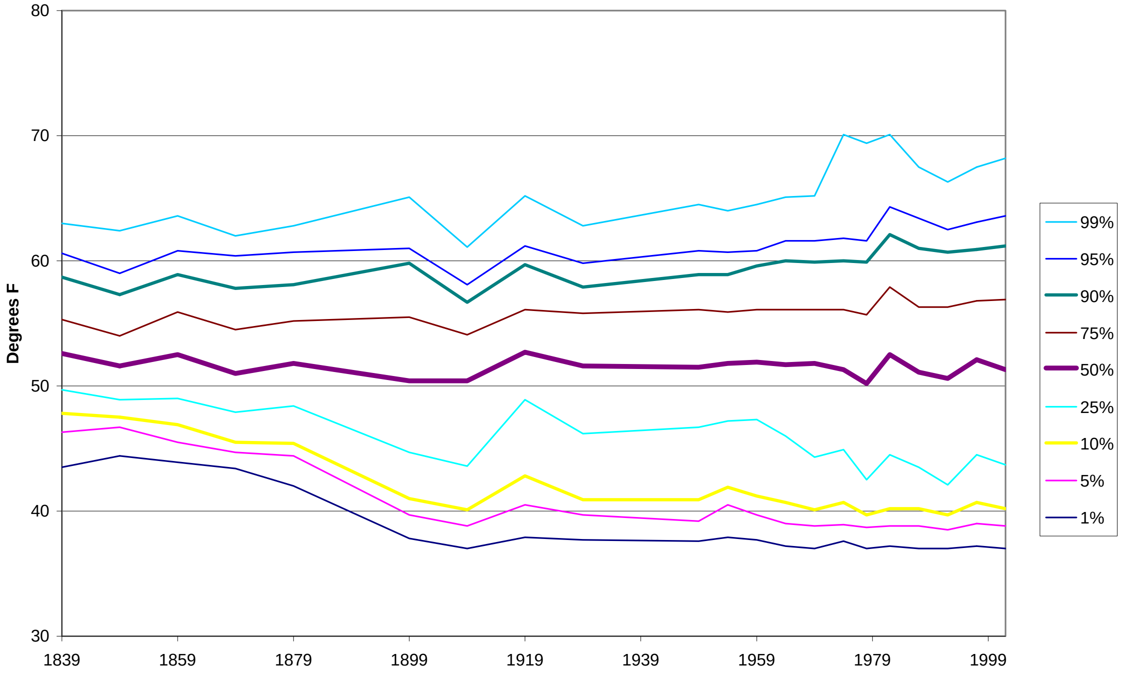
Distribution of Wheat Production by January Precipitation

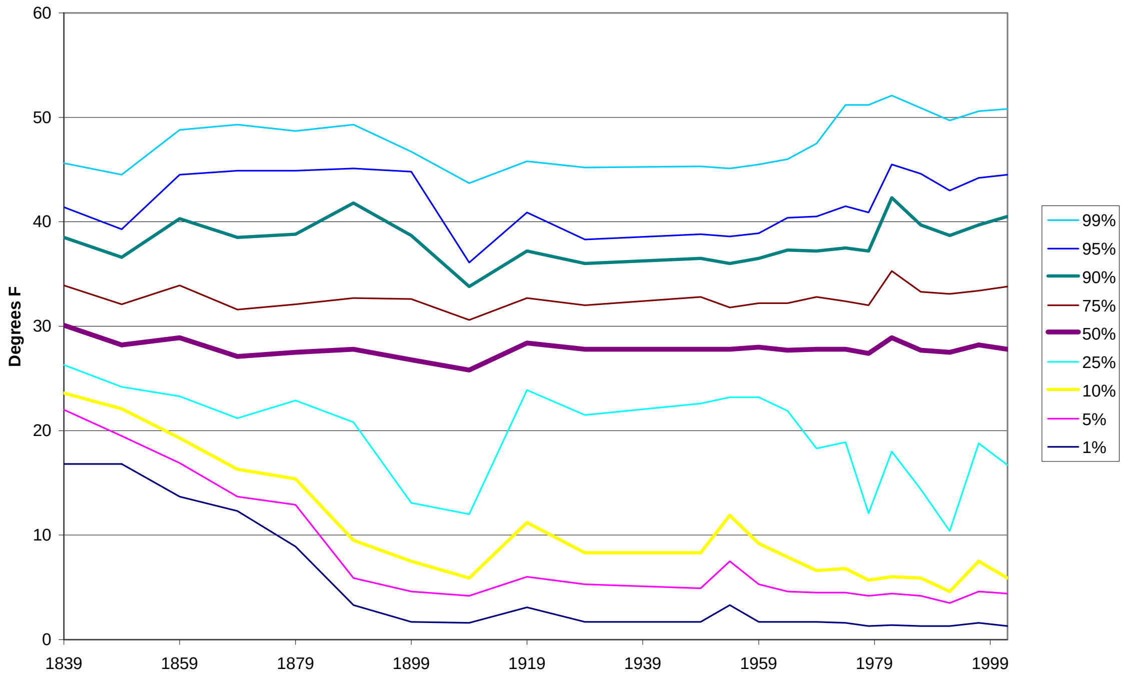


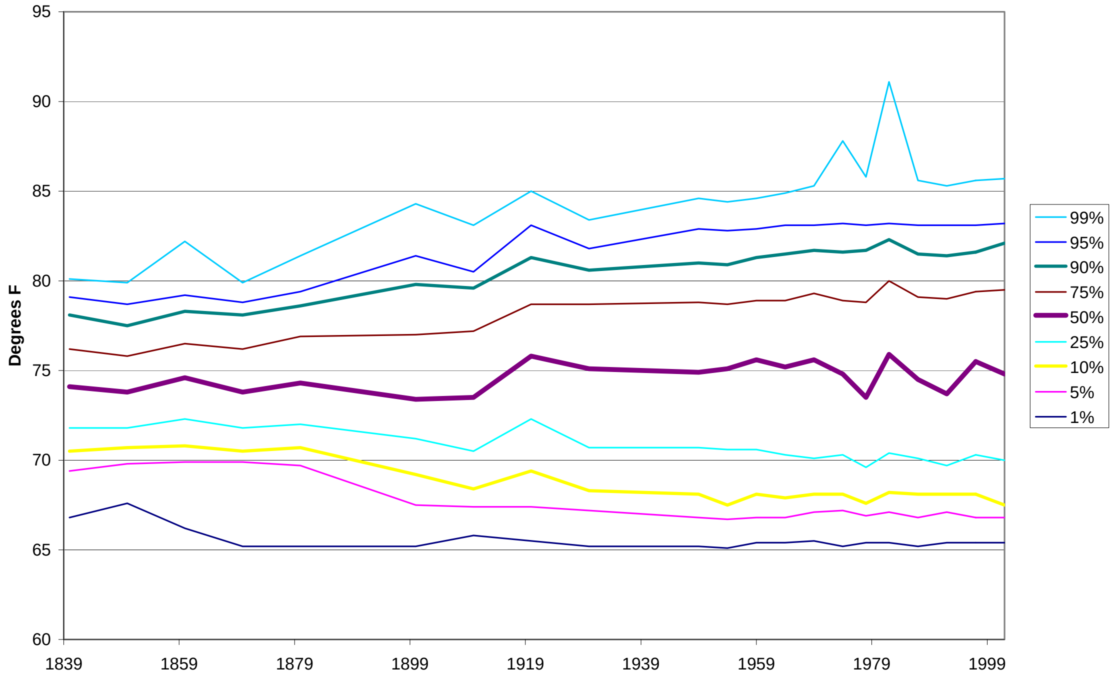
Distribution of Wheat Production by July Precipitation



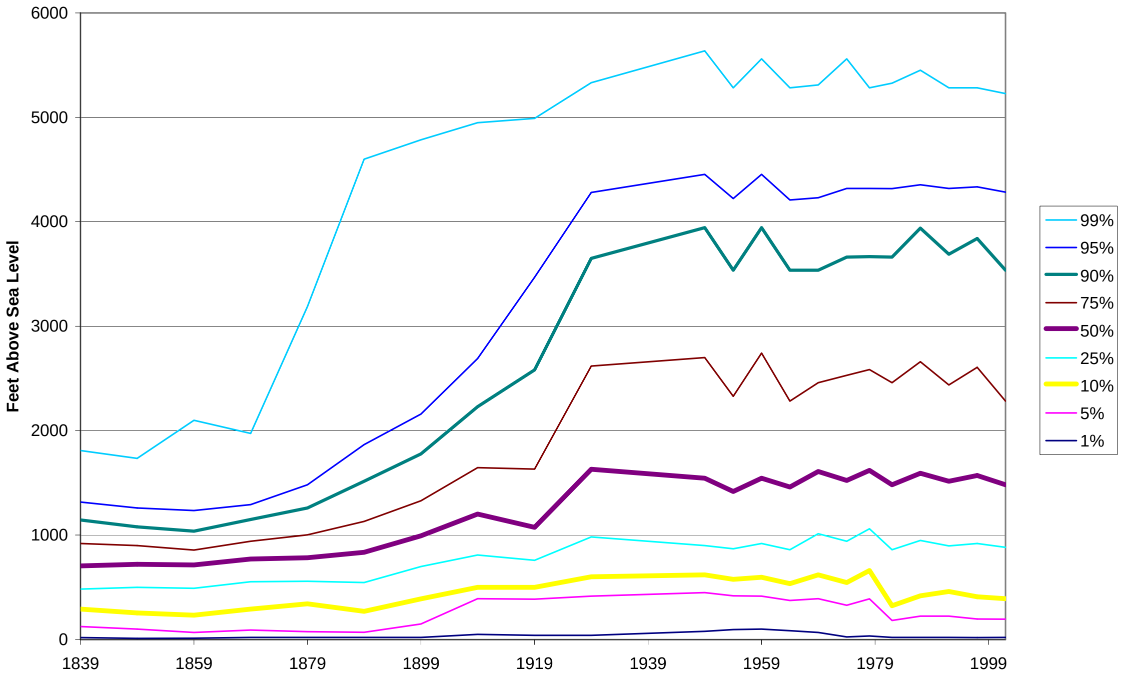
Distribution of Wheat Production by Annual Temperature




Distribution of Wheat Production by January Temperature


Distribution of Wheat Production by July Temperature

Distribution of Wheat Production by Elevation



When settlers moved wheat culture westward, onto the northern prairies, Great Plains, and Pacific coast, they confronted climatic conditions far different from those prevailing in the East or in Western Europe. Early attempts to grow traditional wheat varieties often ended in crop failures and indeed disaster. One example is the early members in Selkirk colony who settled on the Red and Assiniboine Rivers near Lake Winnipeg. Winter wheat, first tried in 1811-12, proved a failure. The fields were resown with spring wheat which, due to drought and cultural problems, also failed. In 1813-14, they resupplied with a small amount of spring wheat seed from Fort Alexander, which yielded sufficient grain for the colony to continue cultivation. But in 1819, a locust plague completely devastated the colony's wheat crop, leaving it without seed. During the dead of winter, a band of the settlers traveled to Prairie du Chien on the upper Mississippi River to secure a replacement seed. After about a decade of hungry times, the colony began to sustain itself, if not flourish.[11]

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[11] Stanley N. Murray, *The Valley Comes of Age: A History of Agriculture in the Valley of the Red River of the North, 1812-1920* (Fargo: North Dakota Institute for Regional Studies, 1967), p. 37; John Perry

Maps of the Great Plains from the 1820s to the 1870s often (mis-) labeled the territory as the "Great American Desert."[12] Though the region was arid, it was not technically a desert. Still it "was long considered to be incapable of agricultural development. Gradually, however, farmers began to displace cattlemen, and by experimentation, attempted to establish a crop system."[13] The first waves of settlers moved into the High Plains during the relatively wet years of the 1880s. The efforts of these farmers, who emigrated mostly from the humid East, to cultivate the soils of the Plains without irrigation constituted:

> ...an experiment in agriculture on a vast scale, conducted systematically and with great energy, though in ignorance or disregard of the fairly abundant data, indicating desert conditions, which up to that time the Weather Bureau had collected. Though persisted in for several years with great determination, it nevertheless ended in total failure.[14]

The successful spread of wheat cultivation across the vast tracts extending from the Texas Panhandle to the Canadian prairies was dependent on the introduction of hard red winter and hard red spring wheats that were entirely new to North America. Over the late nineteenth century, the premier hard spring wheat cultivated in North America was Red Fife (which appears identical to a variety known as Galician in Europe). According to the most widely accepted account, David and Jane Fife of Otonabee, Ontario, selected and increased the grain stock from a single wheat plant grown on their farm in 1842. The original seed was included in a sample of winter wheat shipped from Danzig via Glasgow. It was not introduced into the United States until the mid-1850s. Red Fife was the first hard spring wheat grown in North America and became the basis for the spread of the wheat frontier into Wisconsin, Minnesota, the Dakotas, and Canada. It also provided much of the parent stock for later wheat innovations, including Marquis. At the time of the first reliable USDA survey of wheat varieties in 1919, North Dakota, South

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Pritchett, *The Red River Valley, 1811-1849: a Regional Study* (New Haven, CT: Yale University Press, 1942) pp. 113, 228.

[12] Ian Frazier, *Great Plains*, (New York: Penguin, 1989), pp. 8-9. Walter Prescott Webb, *The Great Plains* (Boston: Ginn, 1959 ed.).

[13] Carter Goodrich, et al., Migration and Economic Opportunity: The Report of the Study of Population Redistribution, (Philadelphia: University of Pennsylvania Press, 1936), p. 207; Alan L. Olmstead and Paul W. Rhode, "Regional Perspectives on U.S. Agricultural Development since 1880," Agricultural History Center Working Paper No. 43, April 1989, pp. 24-25.

[14] Willard D. Johnson, "The High Plains and Their Utilization." in the *Twenty-First Annual Report of the United States Geological Survey to the Secretary of the Interior, 1899-1900*, Part IV,*Hydrography* (Washington, DC: GPO, 1901) p. 681.

Dakota, and Minnesota grew hard red spring and durum wheats to the virtual exclusion of all others.

Another notable breakthrough was the introduction of “Turkey” wheat, a hard red winter variety suited to Kansas, Nebraska, Oklahoma, and the surrounding region. The standard account credits German Mennonites, who migrated to the Great Plains from southern Russia, with the introduction of this strain in 1873.[15] James Malin’s careful treatment describes the long process of adaptation and experimentation, with the new varieties gaining widespread acceptance only in the 1890s. In 1919, Turkey-type wheat made up about “83 percent of the wheat acreage in Nebraska, 82 percent in Kansas, 67 percent in Colorado, 69 percent in Oklahoma, and 34 percent in Texas. It . . . made up 30 percent of total wheat acreage and 99 percent of the hard winter wheat acreage in the U.S.”[16] A similar story holds for the Pacific coast. The main varieties that would gain acceptance in California and the Pacific Northwest differed in nature and origin (Chile, Spain, and Australia) from those cultivated in the humid East in 1839.

As a rule breeders and farmers were looking for varieties that improved yields, were more resistant to lodging and plant enemies, and as the wheat belt pushed westward and northward, varieties that were more tolerant of heat and drought and less subject to winterkill. Canadian experiment station data and other sources show that changes in cultural methods and varieties shortened the ripening period by 12 days between 1885 and 1910. Given the region’s harsh and variable climate, this was often the difference between success and failure.[17] The general progression in varieties allowed the North

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[15] Although the Mennonites were the most notable group of immigrants to bring new seed varieties to the United States, the practice must have been fairly common, especially in the early years of settlement. We have not seen evidence in government reports that would indicate that migrants were more receptive to new varieties released by experiment stations. Carleton R. Ball, “The History of American Wheat Improvement,” *Agricultural History* 4:2 (1930), entire article is pp.48-71;cite is on p. 63.

[16] Karl S. Quisenberry, and L. P. Reitz. "Turkey Wheat: the Cornerstone of an Empire." *Agricultural History* 48:10 (1974): 98-114; James C. Malin, *Winter Wheat in the Golden Belt of Kansas* (Lawrence, KS: University of Kansas Press, 1944).

[17] K. H. Norrie, "The Rate of Settlement of the Canadian Prairies, 1870-1911." *Journal of Economic History* 35:2 (1975): 410-27; Tony Ward, "The Origins of the Canadian Wheat Boom, 1880-1910." *Canadian Journal of Economics* 27: 4 (1994): 864-83. A. H. Reginald Buller, *Essays on Wheat* (New York: Macmillan, 1919), pp. 175-76, credits Marquis with giving adopters about one extra week between harvest and freezeup (which put an end to fall plowing).

American wheat belt to push hundreds of miles northward and westward, and significantly reduced the risks of crop damage everywhere.[18]

One of the most important of the early twentieth century innovations was Marquis, a cross of Red Fife with Red Calcutta, bred in Canada by Charles Saunders. The USDA introduced and tested Marquis seed in 1912-13. By 1916, Marquis was the leading variety in the northern grain belt, and by 1919 its range stretched from Washington to northern Illinois.[19]

The spread of Marquis was not an isolated case. Following extensive expeditions on the Russian plains, Carleton introduced Kubanka and several other durum varieties in 1900.[20] These hardy spring wheats proved relatively rust resistant. By 1903 durum production, which was concentrated in Minnesota and the Dakotas, approached 7 million bushels. In 1904, the region's Fife and Bluestem crops succumbed to a rust epidemic with an estimated loss of 25-40 million bushels, but the durum crop was unaffected. By 1906, durum production soared to 50 million bushels.[21]

The situation was similar in the hard winter wheat belt. Early settlers in Kansas experimented with scores of soft winter varieties common to the eastern states.[22] According to the Kansas State Board of Agriculture, "as long as farming was confined to eastern Kansas these [soft] varieties did fairly well, but when settlement moved westward it was found they would not survive the cold winters and hot, dry summers of the plains."[23] The evidence on winterkill lends credence to this view. Data for four east-central counties for 1885-90 show that over 42 percent of the planted acres were abandoned. For the decade 1911-20, after the adoption of hard winter wheat, the winterkill rate in these counties averaged about 20 percent.[24] Mark Carleton also left his

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[18] J. F. Unstead, "The Climatic Limits of Wheat Cultivation, with Special Reference to North America**,"** *Geographical Journal*, 39:4 (Apr. 1912), pp. 347-366; and 39:5 (May 1912), pp. 421-41.
[19] J. Allen Clark, John H. Martin, and Carleton R. Ball. "Classification of American Wheat Varieties." USDA Bulletin, no. 1074 (1922) p. 901.
[20] Carleton R. Ball, and J. Allen Clark. "Experiments with Durum Wheat," USDA Bulletin, no. 618 (1918).pp. 3-7; J. Allen Clark and John H. Martin. "Varietal Experiments with Hard Red Winter Wheats in the Dry Areas of the Western United States." USDA Bulletin, no. 1276 (1925),.pp. 8-9.
[21] Mark Alfred Carleton, "Hard Wheats Winning Their Way." In USDA *Yearbook, 1914* (Washington, DC: GPO, 1915) pp. 404-08, entire article is pp. 391-420.
[22] Malin, *Winter Wheat*, pp. 96-101.
[23] S. C. Salmon, "Developing Better Varieties of Wheat for Kansas." In *Wheat in Kansas* (Topeka: Kansas State Board of Agriculture, 1920), p. 210; entire article is pp. 210-217.
[24] Malin, *Winter Wheat*, pp. 156-59. Winterkill rates for 1911-20 are calculated using data from Salmon,

imprint on Kansas. In 1900 he introduced Kharkof from Russia. This hard winter wheat adapted well to the cold, dry climate in western and northern Kansas, and by 1914 it accounted for about one-half of the entire Kansas crop.[25]

Drawing on decades of research, S. C. Salmon, O. R. Mathews, and R. W. Luekel, noted that for Kansas "the soft winter varieties then grown yielded no more than two-thirds as much, and the spring wheat no more than one-third or one-half as much, as the TURKEY wheat grown somewhat later."[26] In 1920, Salmon concluded that without these new varieties, "the wheat crop of Kansas today would be no more than half what it is, and the farmers of Nebraska, Montana and Iowa would have no choice but to grow spring wheat" which offered much lower yields.[27]

In addition to introducing new varieties, western farmers experimented with a range of dry farming techniques.[28] The moisture-conserving techniques involved creating a layer of dust to retain precipitation in the soil. Between 1900 and 1930, dry farming was "responsible for a considerable advance into the semiarid region." Yet the new methods created problems too. They quickly destroyed the humus layer and left the soil unprotected against the wind, leading to disastrous effects during the Dust Bowl droughts of the 1930s. "Even after 40 years of trial, a permanently successful system had not been evolved."[29] Adjustment took time.[30]

Mathews, and Luekel, "Half Century of Wheat Improvement," pp. 6, 78-79. The search for varieties suitable for Kansas echoed the earlier experiences of settlers in other states. In the 1840s pioneer farmers attempted to grow winter wheat on the Wisconsin prairie. Repeated failures due to winterkill eventually forced the adoption of spring varieties. Benjamin Horace Hibbard, *The History of Agriculture in Dane County Wisconsin: a Thesis Submitted for the Degree of Doctor of Philosophy, University of Wisconsin, 1902.* Bulletin of the University of Wisconsin, 101; Economics and Political Science Series, 1, no. 2, 67-214. (Madison, WI: 1904), pp. 125-26.

[25] Carleton, "Hard Wheats," pp. 404-8.

[26] S. C. Salmon, O. R. Mathews, and R. W. Luekel. "A Half Century of Wheat Improvement in the United States" In A. G. Norman, ed., *Advances in Agronomy*, pp. 1-145. Vo. 5. (New York: Academic Press, 1953), p. 14.

[27] Salmon, "Developing Better Varieties," pp. 211-12.

[28] Zeynep K. Hansen and Gary D. Libecap, "Small Farms, Externalities, and the Dust Bowl of the 1930," *Journal of Political Economy*, 112:3 (2004): 665-94; Zeynep K. Hansen and Gary D. Libecap, "The Allocation of Property Rights to Land: US Land Policy and Farm Failures in the Northern Great Plains," *Explorations in Economic History*, 41:2 (2004): 103-29; Gary D. Libecap and Zeynep K. Hansen, "'Rain Follows the Plow' and Dryfarming Doctrine: The Climate Information Problem and Homestead Failure in the Upper Great Plains, 1890-1925," *Journal of Economic History*, 62:1 (2002): 86-120.

[29] Goodrich, *Migration*, pp. 207, 215.

[30] Mary W. M. Hargreaves, *Dry farming in the northern Great Plains, 1900-1925*, (Cambridge, Harvard University Press, 1957) and Mary W. M. Hargreaves, *Dry farming in the Northern great plain: years of readjustment, 1920-1990* (Lawrence, KS: University Press of Kansas, 1993).

Wherever it is feasible, farmers prefer to grow winter wheat instead of spring wheat. Winter wheat generally offers higher yields and is much less subject to damage from insects and diseases. The problem is that in colder climates winter wheat suffers high losses to winterkill. The agronomy literature commonly recognizes that the development of more hearty winter varieties that could be grown in harsher climates was a great achievement. Just how much land was affected by this fundamental change in farming practices? County-level data on spring and winter wheat production found in the agricultural censuses of 1869 and 1929 allow us to map the northern shift in the "spring wheat"-"winter wheat" frontier in the plains and prairie states.[31]

Figure 4 reports estimates (derived from regression analysis) for each degree of longitude between 87º and 105º of the latitude where spring wheat output equaled winter wheat output in 1869 and 1929.[32] In both years, except in isolated pockets, spring wheat output exceeded winter wheat output north of the estimated frontier, and winter wheat dominated south of the frontier. In most places the break was sharp with a narrow transition zone. Farmers grew little winter wheat just 30 miles above the demarcation line and little spring wheat 30 miles below the line. In 1869, the frontier generally followed the 40th parallel for longitudes between 87º and 94º and then swept down to the southwest across eastern Kansas. (Given the prevailing limits of wheat cultivation, the frontier cannot be mapped for more western longitudes in 1869.) By 1929, the spring wheat frontier had shifted dramatically to the north and west. In that year, the frontier followed roughly the 43rd parallel between 87º and 100º and then took a southwest course. Thus, over this sixty-year period, the frontier crept northward across most of Kansas and Iowa, as well as southern Nebraska. The area between the 1869 and 1929 "spring wheat"-"winter wheat" frontiers accounted for almost 30 percent of U.S. wheat output in 1929!

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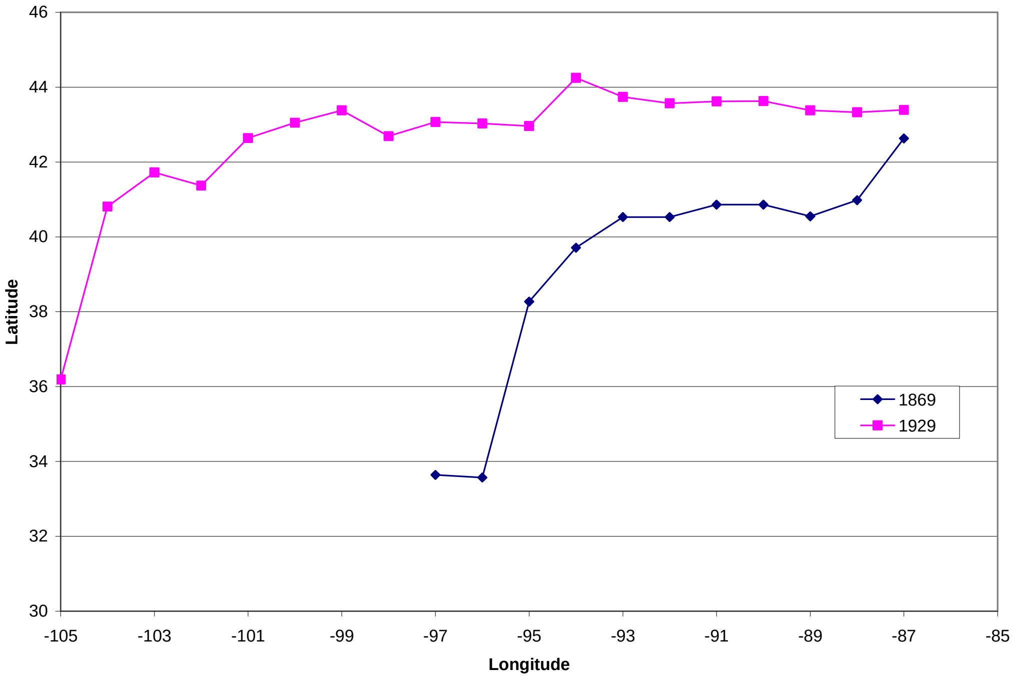
[31] The 1869 data were provided by Craig, Haines, and Weiss, *Development, Health, Nutrition*. The 1929 data are from U.S. Census Bureau. 15th Census 1930, *Agriculture*.

[32] To derive the estimates, we performed logit regressions for the winter wheat share of wheat output in each county in a given longitude grouping. We again used the county seat as a measure of the county's location. For each degree of longitude, we used the latitude where the winter wheat share equaled one-half.

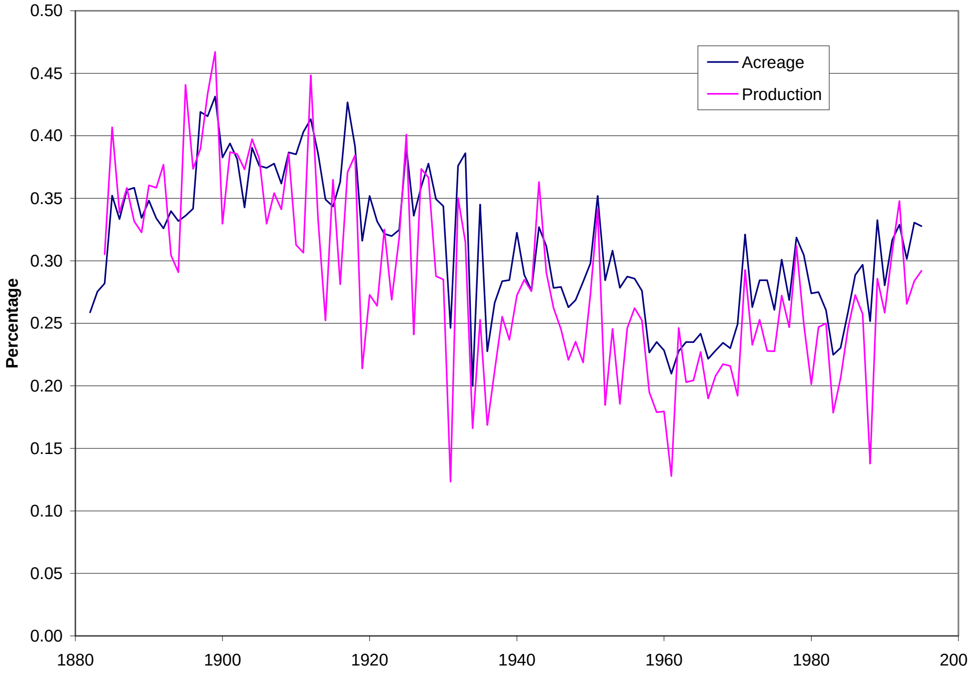
Figure 4: Spring Wheat- Winter Wheat Frontier, 1869 and 1929



Note: North of the frontier for any given longitude spring wheat output exceeds winter wheat output except in isolated pockets.

Figure 5 charts the ratio of spring wheat to total wheat acreage and production in the United States. It uses the best available data from the USDA. Official revised data segregating the two types of wheat begin in 1909. Earlier unadjusted data from USDA allow us to extend the series back to the 1880s. Note the acreage share of spring wheat is typically greater than its production share, consistent with lower yields per acre for spring wheat relative to winter wheat. The spring wheat shares of acreage and output rose over the late nineteenth century as grain production moved into the northern Great Plains. This exerted a drag on overall wheat yields. The share declined subsequently, due in part to the northward shift in the spring-winter wheat line. The low spring wheat shares in the 1930s are related to the dust bowl era droughts. Note these series cover U.S. production only. Including Canadian output would significantly increase the spring wheat share throughout the period. (For an analysis including Canadian wheat, see the maps and figures in the Appendix.)

Figure 5: Spring Wheat as a Share of U.S. Output and Acreage



Sources: USDA *Crop Reporter*, Feb. 1908 p. 13, USDA *Yearbook 1916*, p. 573; *Yearbook 1920* table 21, *Commissioner of Agriculture 1886* p. 410.

The biological transformation in the nineteenth and early-twentieth century grain-growing was not unique to the United States, but rather was part of a worldwide process. The farmers who extended the wheat frontier in Canada, Australia, Argentina, and Russia in the nineteenth century, faced similar challenges of producing in new and harsh environments. In all of these areas, the first attempts to grow wheat by new immigrants failed. Success depended on biological innovation. Farmers and plant breeders from all these countries scoured the globe for varieties that might meet local needs, they selected and increased the seeds from particularly promising plants, and by the end of the nineteenth century a number of scientists were creating hybrids that combined the favorable traits of varieties drawn from around the world. This was a purposeful and sophisticated process lead by men whom plant scientists today still revere as the pioneering giants of their discipline. The challenges differed with farmers in Canada, like their brethren in the northern Great Plains of the United States, requiring early and fast ripening hardy spring wheats. In Australia the most important innovations developed by William Farrer pushed wheat into hot and arid regions previously to hostile for wheat.

Although the breeding efforts in different countries evolved in ways reflecting their individual national character and environmental conditions, by the end of the nineteenth century, breeding had become a global enterprise with the exchange of ideas, scientists, and germstock between every continent. These exchanges were facilitated by the research and extension programs that flourished in every major wheat-producing nation (and within the United States in every important wheat-producing state). The scientific community functioned more efficiently as personal contacts, informal networks, and professional journals united researchers into a closely knit community.[33]

The global shift of wheat cultivation had dramatic effects on typical growing conditions, with a movement onto drier and colder lands. Table 2 uses data on the distribution of world wheat production across different geo-climatic zones to document these changes.[34] World production in 1926-30 was distributed to lands that, on average, were 5.5°F colder and received 4.3 fewer inches of precipitation than the areas where wheat had been cultivated in 1866-70. Given large and expanding production in Europe, the changes in the conditions facing farmers near the frontier were significantly greater than the changes displayed in Table 2.[35] 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. Clearly, global wheat cultivation was shifting to poorer lands, making the 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.

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[33] For a discussion of the international exchange of knowledge and germplasm see Alan L. Olmstead and paul W. Rhode, "Biological Globalization: The Other Grain Invasion," pp. 115-140 in Timothy J. Hatton, Kevin H. O'Rourke, and Alan M. Taylor, eds., *The New Comparative Economic History: Essays in Honor of Jeffrey G. Williamson* (Cambridge, MA: MIT Press, 2007).

[34] 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* 13:6 (March 1937): 265-308. 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 subunits, 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.

[35] The fall in the average temperature was also dampened by the movement of production into hotter regions of Australia, the United States, etc.

Table 2: Changing Climatic Conditions of Global Wheat Production

	Annual Temperature (Degrees F)	Pre-harvest Temperature (Degrees F)	Annual Precipitation (Inches)	Yield in Bushels Per Acre
1866-70	57.7	68.2	28.9	20.7
1886-90	54.9	65.4	26.8	17.2
1910-14	53.1	64.9	25.2	15.7
1926-30	52.2	64.4	24.6	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.

These changes in the average climatic conditions of wheat production were the predictable consequences of lower transportation costs opening the continental interiors to profitable production. 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 in precipitation and temperature.... These climatic characteristics are generally unfavorable for wheat yields.[36]

The reductions in transportation costs, together with biological learning, induced a global shift of wheat cultivation from maritime areas with temperate climates to interior regions with harsher continental climates.

MAIZE

As with wheat, the location of U.S. corn production shifted dramatically over the late nineteenth and early twentieth centuries. Table 3 provides the mean latitudes and longitudes of the U.S. corn crop from 1839 to 1929. In 1839, the geographic center of corn production was near Richmond, Kentucky. This was far to the west of the center of wheat production, reflecting corn's status as a frontier crop at this time. By 1929, the center of corn production had moved to the vicinity of Hannibal, Missouri. Over the entire period, the center of production had moved 425 miles to the west northwest.

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

Table 3: Geographic Center of Corn Production, 1839-1929

	North Latitude			West Longitude				
	deg	min	sec	deg	min	sec	Miles of Movement	
1839	37	21	29	83	53	6	1839 - 1849	54
1849	37	40	33	84	47	47	1849 - 1859	78
1859	38	5	4	86	8	4	1859 - 1869	65
1869	38	46	10	86	57	56	1869 - 1879	120
1879	39	27	34	89	1	13	1879 - 1889	93
1889	39	19	15	90	45	46	1889 - 1899	20
1899	39	22	50	90	23	57	1899 - 1909	9
1909	39	25	20	90	14	15	1909 - 1919	13
1919	39	20	3	90	1	6	1919 - 1929	66
1929	39	38	2	91	11	41	1839 - 1929	425

Sources: See Table 1.

Latitude crucially shaped the spread of corn cultivation. In a well-known article, Richard Steckel invoked the photoperiodic properties of maize to explain the east-west pattern of U.S. migration during the nineteenth century.[37] Corn is classified as a short-day plant. Such plants flower after the number of hours of daylight falls below a certain maximum threshold. For corn, the shortening days in the latter part of summer trigger flowering. Long-day plants such as wheat and small grains, by way of contrast, time their flowering to occur after the number of hours of daylight rises above a certain minimum. Steckel further observes that "Long-day or short-day plants that are grown outside their latitude of adaptation mature too early or too late for optimal performance."[38]

Steckel quantifies the effect of growing the "right" corn by using historical data from experiment station trials. Between 1888 and 1894 the Illinois Agricultural Experiment Station at Champaign tested a variety of corn seeds adapted "to about 80 different locations" in the Midwest and Northeast. Drawing on these field trials, Steckel's econometric analysis found that the "yields of seeds adapted 250 miles south and 250 miles north were only 62 and 72%, respectively, of the yield of seed adapted to Champaign. Yields of seeds adapted up to 250 miles east were slightly higher than those adapted to Champaign, whereas the yields of seed adopted 250 miles west was 93% of the yield of seeds adapted to Champaign."[39] Here is solid evidence of the importance of

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[37] Richard Steckel, "The Economic Foundations of East-West Migration during the Nineteenth Century" *Explorations in Economic History* 20 (1983): 14-36.

[38]. Steckel, "Economic Foundations," p. 20.

[39] Steckel, "Economic Foundations," p. 22.

matching corn varieties to geoclimatic conditions. For corn, north-south variations mattered significantly, but east-west variations were relatively minor.

Steckel argued that pioneering farmers learned that their seed corn was adapted to the seasonal daylight conditions of their own latitude. When moving to new areas of settlement, they "probably took their own supplies of seed grain." Thus they would be disinclined to change latitudes significantly for fear that their seeds would generate substantially lower yields. "Farmers who went too far north or south had poor yields and sent relatively unfavorable reports back to the community from which they left."[40] Although westward settlement occurred across a broad front, for many it involved movement along an east-west line.

The Figure 6 replicates the previous exercise by showing the changing distribution of U.S. corn production by location and climatic conditions. Again, it is important to recall the corn crop expanded tremendously after 1839. The crop in the 1920s was about 7 times larger than in 1839.

The panel on longitude captures the westward shift in corn production—a movement of the median location by about 6 degrees between 1839 and 1929. But there was also a shift in median latitude of 2.5 degrees, or roughly 200 miles to the north. In addition, the range of latitudes widened commensurately. There were significant accompanying changes in climatic conditions. The median annual temperature under which corn was grown fell by almost 5 degrees F. from 56.3 degrees in 1839 to 51.5 degrees in 1929. (This is of the same magnitude but in the opposite direction of the change that the IPCC predicts will occur in North America over the next century.) Median annual precipitation fell by almost 9 inches, from 43.9 inches in 1839 to 34.8 inches in 1929. Median elevation rose by 180 feet and again almost none of the crop was produced in areas directly affected by the anticipated rise in the sea level resulting from global warming.

The movement of corn production to new drier and colder environments required biological innovation. M. L. Bowman and B. W. Crossley observed in 1908 that "the cultivation of corn has been gradually extended northward in the United States. Today this cereal is grown successfully, where twenty-five years ago its cultivation was

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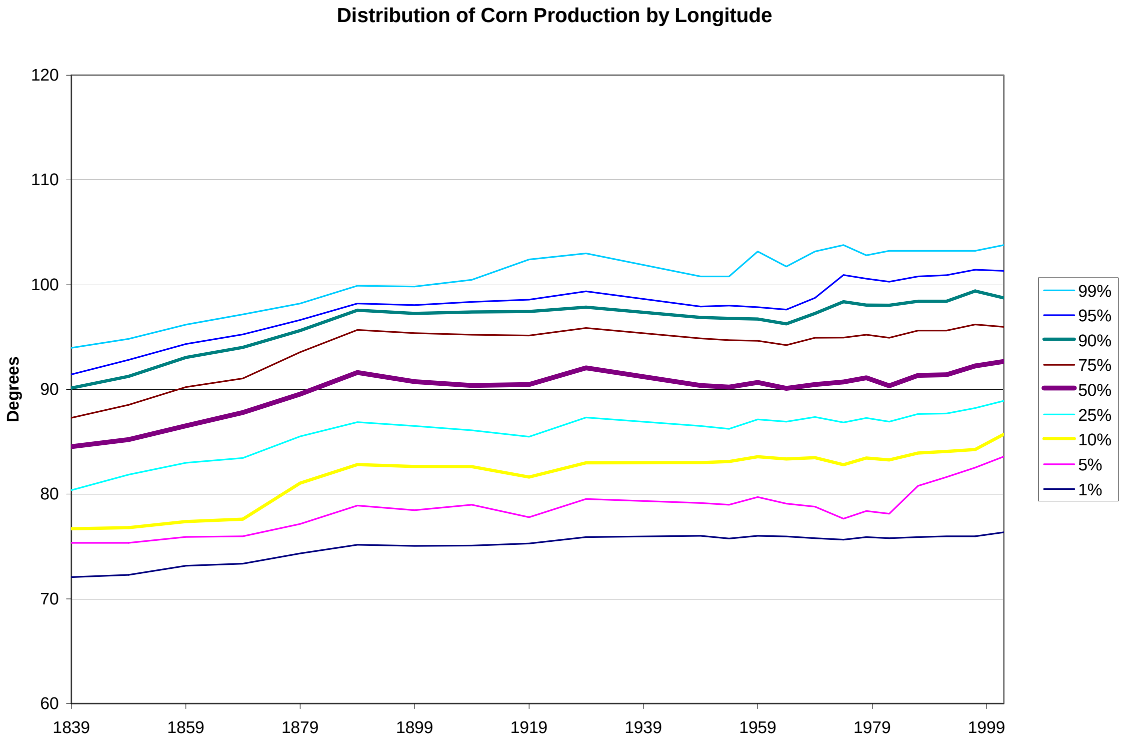
[40] Steckel, "Economic Foundations," p. 23.

impossible."[41] It is possible to identify specific breakthroughs that facilitated the shift of the corn belt several hundred miles to the north. Of special significance was the work of Andrew Boss, C. P. Bull, and Willet Hays at the University of Minnesota who developed Yellow Dent Minnesota No. 13 and Yellow Dent Minnesota No. 23. "These varieties had remarkable early ripening properties that reduced the ripening time from 120 to 125 days to about 90 days (for No. 23). These and other early ripening varieties also allowed farmers in the Canadian plains to grow corn for ensilage."[42]

Figure 6: Distribution of U.S. Corn Production, 1839-2002



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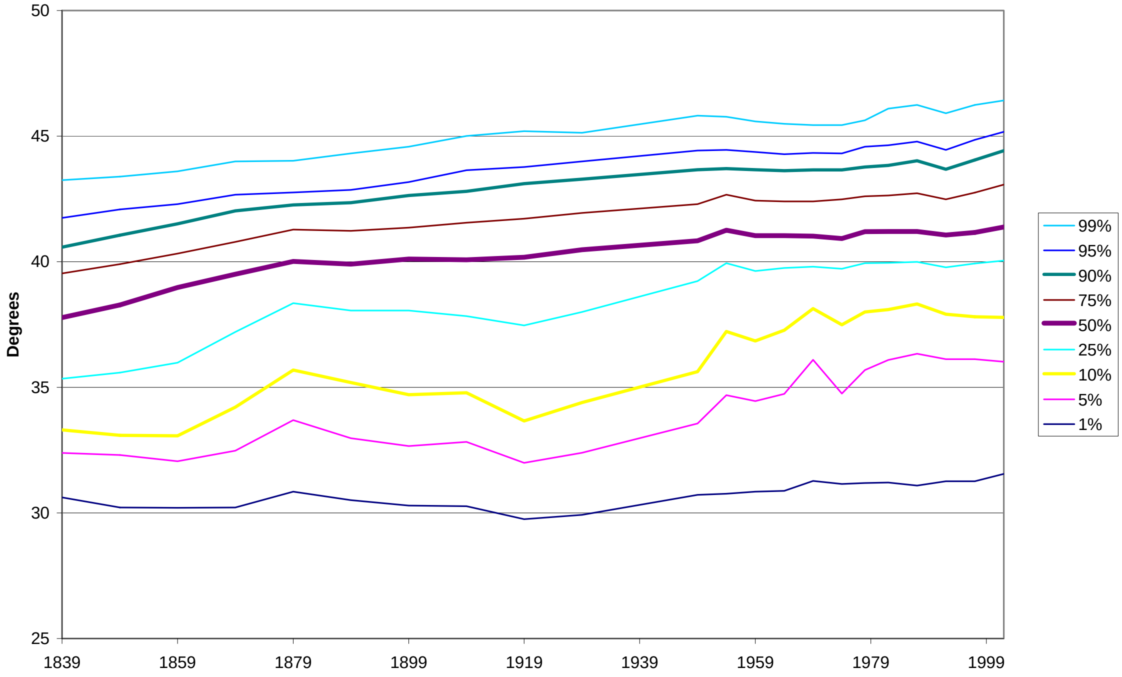
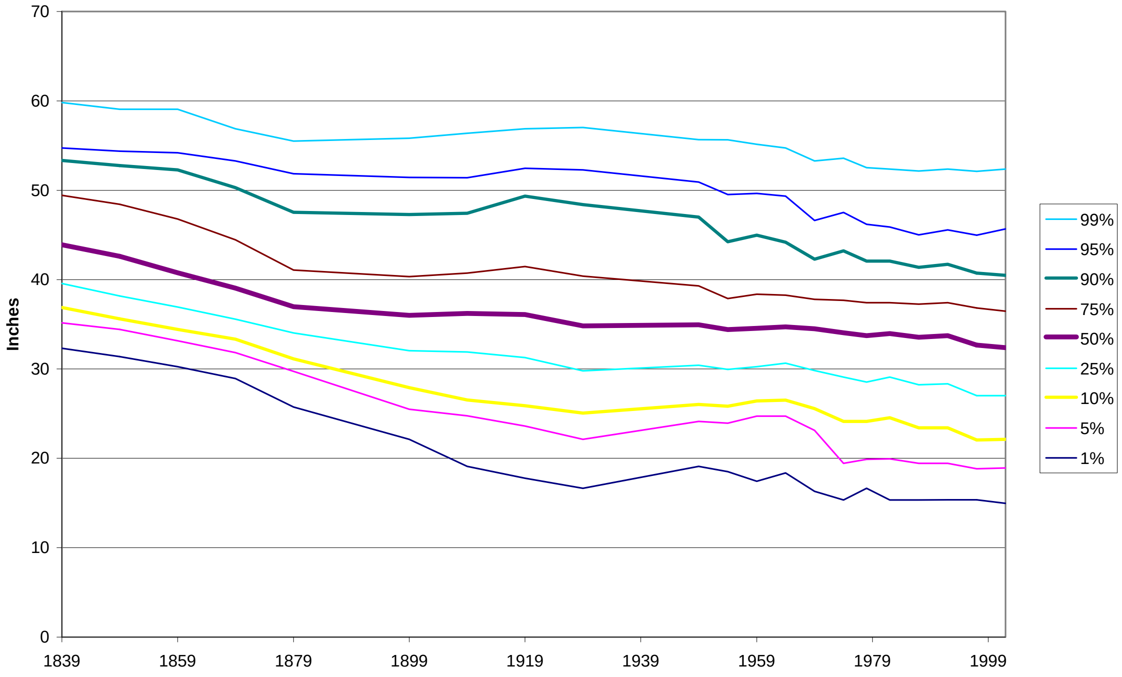
[41] M. L. Bowman and B. W. Crossley, *Corn: Growing, Judging, Breeding, Feeding, Marketing* (Ames, IA, Self-published, 1908), p. 90.
[42] A. H. Reginald Buller, *Essays on Wheat* (New York: MacMillan Company, 1919), pp. 187-90.

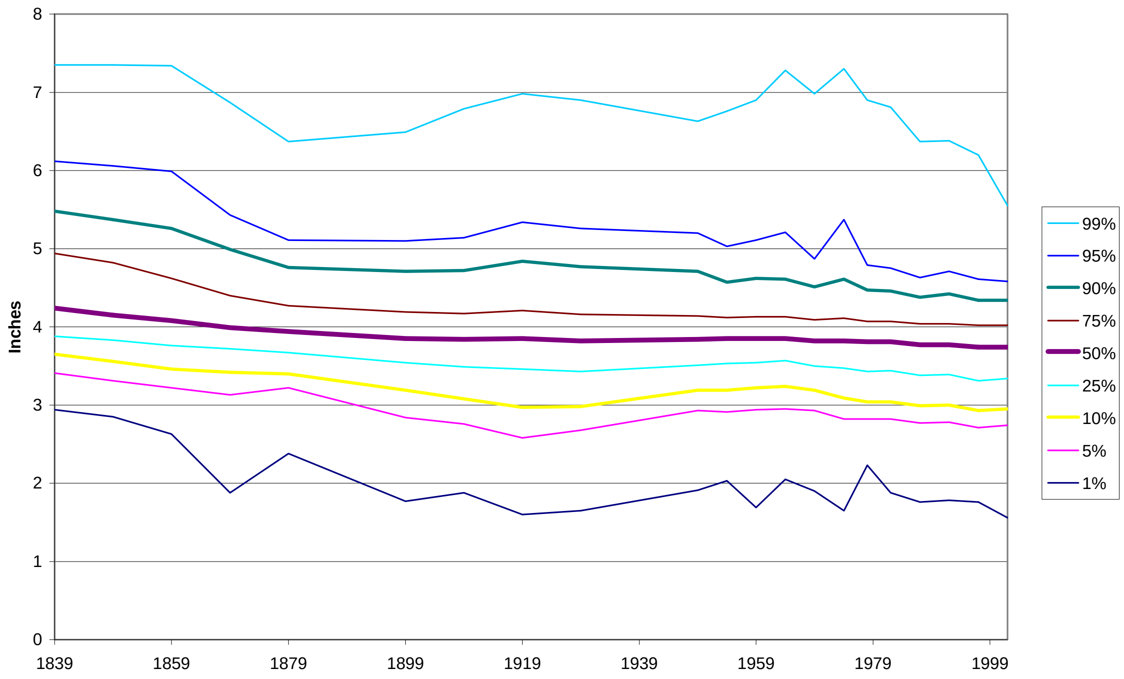
Distribution of Corn Production by Latitude



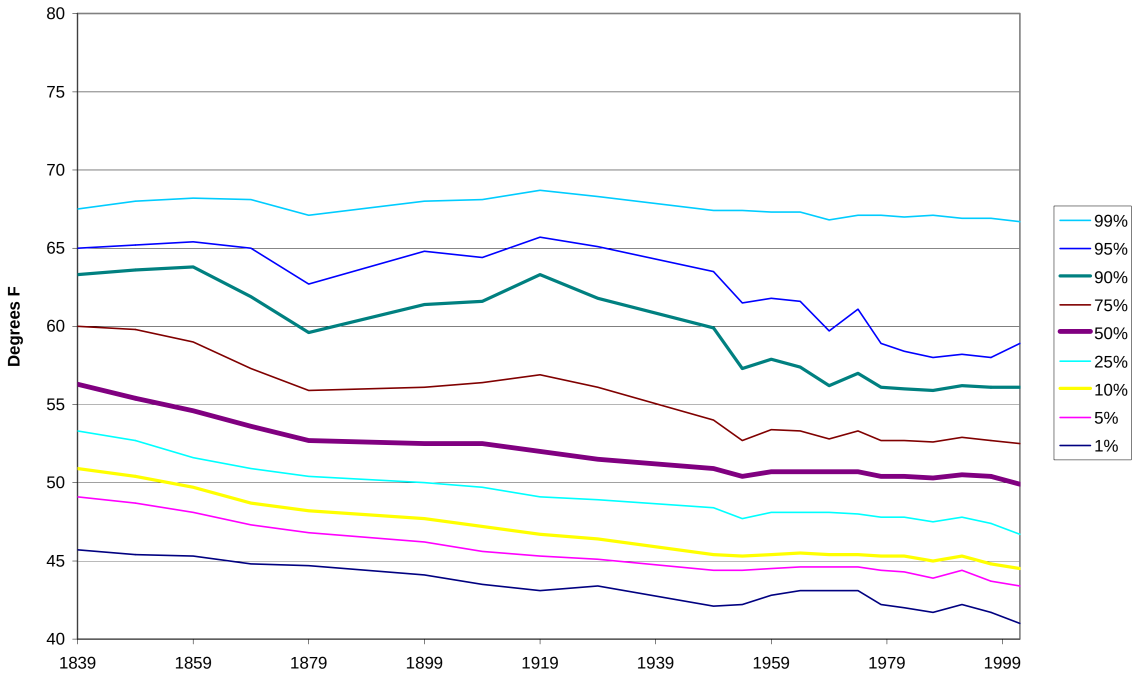
Distribution of Corn Production by Annual Precipitation



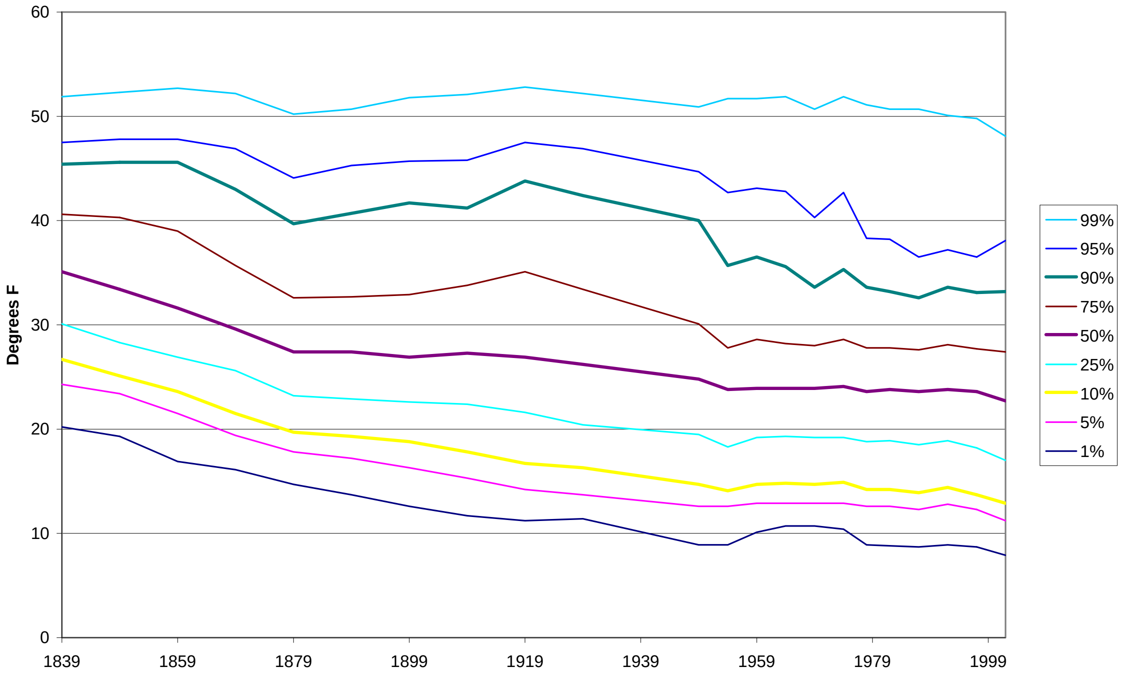
Distribution of Corn Production by July Precipitation



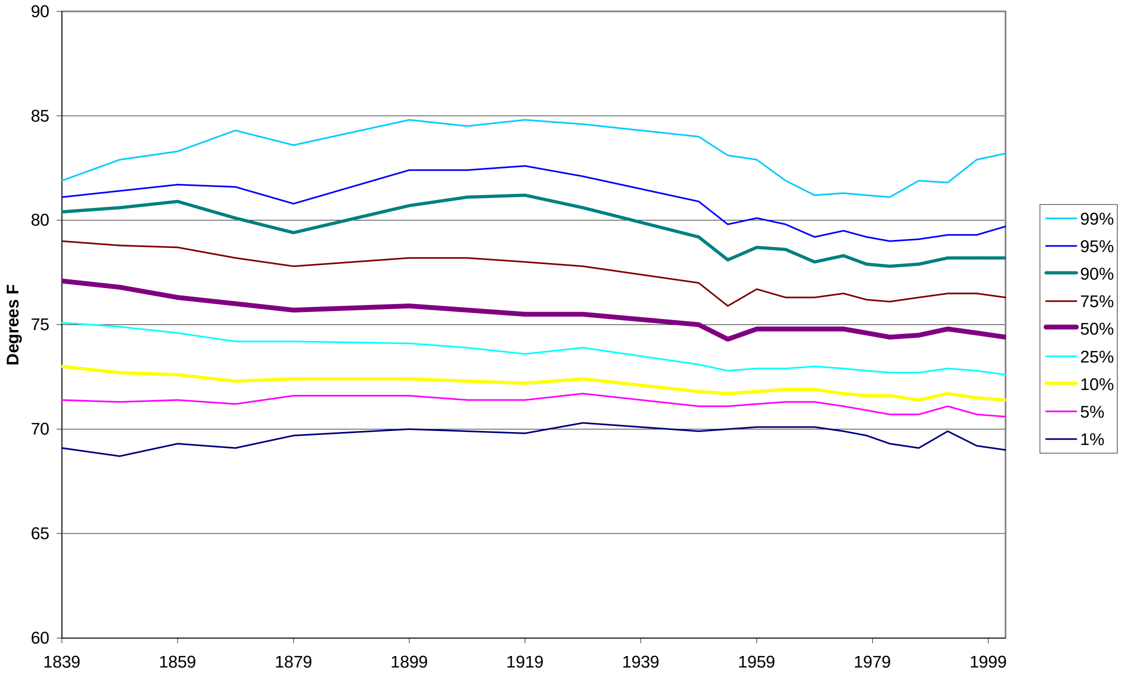
Distribution of Corn Production by Annual Temperature

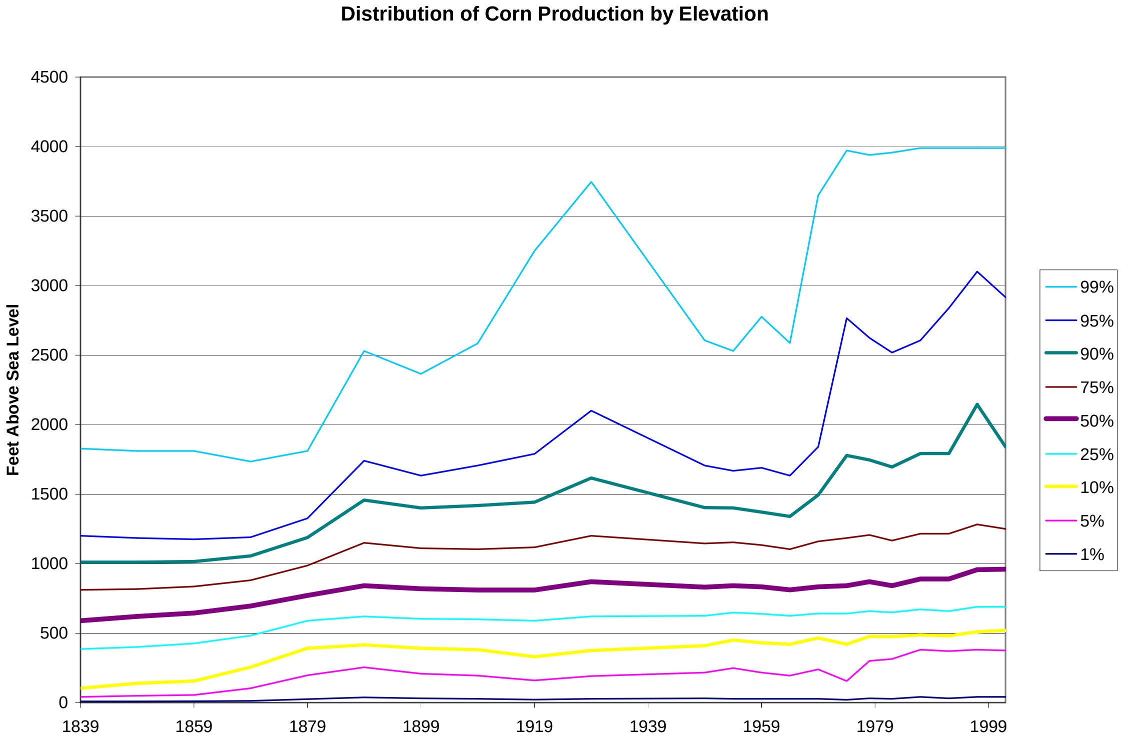


Distribution of Corn Production by January Temperature



Distribution of Corn Production by July Temperature





According to Andrew Boss and George Pond, "the development of early-maturing varieties of corn combined with adapted hybrid varieties, and improved cultural practices are steadily drawing the corn belt northward and westward into the Spring Wheat area. Accompanying this movement has been a steady increase in cattle and hog production in the area which furnished the chief outlet for the corn crop."[43] Minnesota 13 was a potent factor in pushing corn grown for grain 50 miles northward in a single decade.[44] We can build on our earlier analysis of the shifting spring wheat-winter wheat frontier to quantify these claims regarding the movement of the corn-wheat frontier. Using county-level

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[43] Andrew D. Boss and George A. Pond, *Modern Farm Management: Principles and Practice* (Saint Paul. MN: Itasca Press, Webb Publishing, 1951), p. 65; A. Forrest Troyer and Lois G. Hendrickson, "Background and Importance of Minnesota 13' Corn" *Crop Science* 47 (May 2007), pp. 905-14.

[44] See A. Forrest Troyer, "Persistent and Popular Germplasm in Seventy Centuries of Corn Evolution, in C. Wayne Smith, Javier Betrán, and E. C. A. Runge, eds., *Corn: Origin, History, Technology, and Production* (New York: Wiley, 2004). p. 176 (entire chapter is pp. 133-231); W. M. Hays, *Breeding Animals and Plants* (St. Anthony Park, MN: Farm Students' Review, 1904). pp. 19, 82. Minnesota 13 was selected over several years from local seed purchased in 1893. It was first released in 1897. A number of even earlier Dents were subsequently developed at experiment stations in Minnesota, the Dakotas, and Montana. George W. Will, *Corn for the Northwest* (St. Paul, MN: Webb Publishing, 1930), pp. 65, 85-88, 147.

census data for 1869 and 1929, we can examine, for longitude groups, at what northern latitude the value of corn production equaled that of wheat production.[45] Given the focus on the northern limit, we restrict the analysis to latitudes above 40 degrees. To compensate for the effects on the sample size, we estimate the frontier using regressions on overlapping two-degree longitude bins.

The results, reported in Figure 7, are striking. In 1869, the frontier basically followed a line just south of the 43rd parallel over the longitudes from 87 degrees to 95 degrees and then turned south. By 1929, the frontier was pushed near the Canadian border for these longitudes and remained above the 43rd parallel until 100 degrees of longitude (the line where the "Great American Desert" began.) Thus, an enormous area including most of Minnesota, South Dakota, and Nebraska shifted from the wheat belt to the corn belt over this sixty-year period. The northern shift of the corn frontier was celebrated in construction of the famous Corn Palace at Mitchell, South Dakota (latitude, 43.7034; longitude, 98.0626) in 1892. [46] Without researchers developing earlier maturing varieties this shift would not have been possible.

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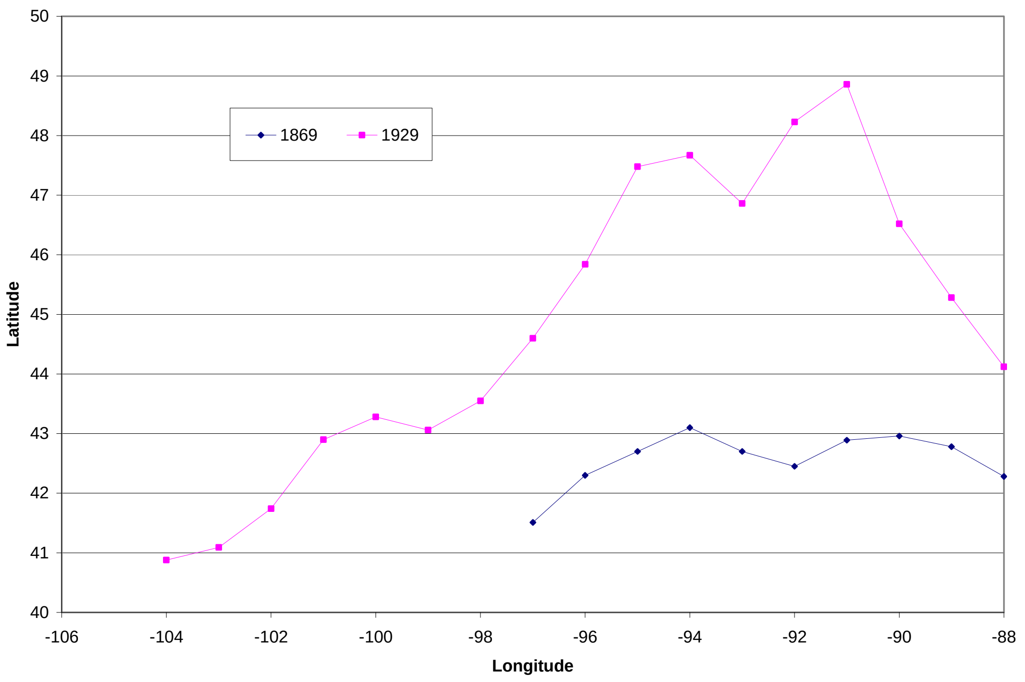
[45] These value calculations use prevailing crop national prices: specifically, 105 cents per bushel of wheat and 77 cents for corn in 1929 and 93 cents for wheat and 73 cents for corn in 1869. This is biased against the expansion of the corn area because the price of corn relative to wheat in 1929 was lower than in 1869.

[46] The Midwest was home to many such fanciful structures decorated with tapestries of corn. The original was built in Sioux City, Iowa in 1887. Charles S. Plumb, *Indian Corn Culture* (Chicago: Breeder's Gazette Print, 1895), pp. 230-32.

Figure 7: Corn-Wheat Frontier, 1869 and 1929



Sources: See Table 1.

COTTON

Cotton, the country's third major nineteenth century staple crop, also required extensive adaptation as its culture spread across the American South and Southwest. According to J. O. Ware, a leading USDA cotton expert, the varieties that became the basis for the South's development were a distinctly "Dixie product." "Although the stocks of the species were brought from elsewhere, new types, through [a] series of adaptational changes, formed this distinctive group the final characteristics of which are a product of the cotton belt of the United States."[47] This process of molding cotton was repeated over and over again as new varieties were introduced and as production moved into new areas. According to Ware, "The vast differences in climate and soil that obtain over the Cotton Belt undoubtedly brought about a kind of natural selection which

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[47] Jacob Osborn Ware, "Origin, Rise and Development of American Upland Cotton Varieties and Their Status at Present." University of Arkansas College of Agriculture, Agricultural Experiment Station Mimeo, 1950, p. 1.

eliminated many of the kinds that were tried, while others became adapted to the several conditions under which they were grown and selected over a period of years."[48]

Cottons cultivated in the United States belong to one of two species. Sea Island (*G. Barbadense*) was grown primarily along the coasts and on the offshore islands of Georgia, South Carolina, and Florida. Sea Island produced high quality, long staple fibers (over 1¼ inches), but was low yielding and difficult to pick. Cottons of the second and more important species (*G. Hirsutum*) were commonly referred to as upland cottons because they were grown in the more variable climates away from the coast. As of the turn of the twentieth century, cotton experts grouped the upland varieties into eight general types. Most of these types could be developed to fit specific environmental and economic situations and would be ill suited for other conditions. None of these cottons were native to British North America.

Adaptation was essential for the successful cultivation of upland cotton. In its native environment in Central America, *G. Hirsutum* was a frost-intolerant, perennial shrub with short-day photoperiod response. As a short-day plant, its flowering was triggered when the nights began to grow longer and cooler in the late summer or autumn. This strategy was adapted to a semi-tropic, semi-arid environment where the rains came in the autumn. The greater variation in day length over the seasons at the higher latitudes of the American South meant that the date with the right conditions to trigger flowering occurred later in the year. This meant that many of the introduced cotton varieties either did not mature before the first frost set in or did not flower at all. Initial attempts to grow upland cotton in the areas that now constitute the United States faced severe challenges. Success depended on finding a mutation/cross or a variety with the appropriate photosensitivity characteristics. "Following generations of repeated selection, these initial stocks were molded into early maturing, photoperiod-insensitive cultivars adapted for production in the southern United States Cotton Belt."[49] Adaptation was made easier because, as John Poehlman and David Sleper note, the cotton stocks first introduced to

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[48] J. O. Ware, "Plant Breeding and the Cotton Industry," *Yearbook of Agriculture, 1936* (Washington, DC: GPO, 1936), p. 659 (657-744); R. B. Handy, "History and General Statistics of Cotton," in Dabney, *The Cotton Plant: Its History, Botany, Chemistry, Culture, Enemies, and Uses* USDA Office of Experiment Stations, Bulletin No. 33 (Washington, DC: GPO, 1896), pp. 17-66.

[49] John Milton Poehlman and David Allen Sleper, *Breeding Field Crops*, 4th Ed. (Ames, IA: Iowa State Univ. Press, 1995), 376; Stephens, "Some Observations of Photoperiodism," pp. 409-18.

the region "were largely mixed populations with varying amounts of cross-pollination and heterozygosity that gave them plasticity and potential for genetic change."[50]

Cotton breeders confront a number of trade-offs because improving one plant characteristic often requires sacrificing another desirable quality. Breeders strive for high yields, long staple lengths, soft and strong fibers, good spinning characteristics, ease of picking, high lint-to-seed ratios, whiteness, and more. In addition, breeders work to develop cotton varieties to match local soil and climatic conditions (especially the length of the growing season), to resist specific diseases and pests, survive high winds, and to appeal to special market niches. The importance of wind resistance became more significant as cotton cultivation moved onto the Texas plains, and the incentive to develop cotton that could be picked more rapidly increased as wages rose.

In the antebellum period, the South developed and grew three main "types" of upland cotton: the Petit Gulf or long-limbed cottons, which were late maturing, spreading plants producing long staple fibers, and best suited for fertile lands; the cluster cottons, based on Sugar Loaf (1843) and Boyd's Prolific (1847), which were earlier, more compact plants producing shorter staple lint; and semi-cluster cottons, another variant of Boyd's Prolific with a more moderate tendency for the bolls to cluster. The 1870s saw the development of two additional types -- Peterkin and Eastern Big Boll. Three more types gained prominence over the late nineteenth century -- Early or King, Long Staple or Allen, and Western Big Boll.

The types known as Western Big Boll, Stormproof, and Texas Big Boll cotton were noted for two characteristics. They were resistant to shedding or breaking in high winds, and they were relatively easy to pick because of their large bolls. Whereas, the eastern big boll cottons likely evolved from a Mexican variety imported in the 1850s by a Georgia planter named Wyche via Algeria, Texas big boll cotton likely evolved out of varieties imported directly from the dry plains of northern Mexico. The process of selection was similar in both regions. "Under the conditions of the great climatic change, pronounced environmental shock was effective in breaking up or isolating favorable responding genotypes. These better balanced and, therefore, more fruitful forms were

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[50] Poehlman and Sleper, *Breeding Field Crops*, p. 376. They further note that "the adjustments were hastened by the contributions of large numbers of early cotton breeders who worked without the genetic guidelines available to cotton-breeders today."

readily recognized by growers who would save the seed from them. In this way desirable plant habit having the necessary production characteristics for the new adaptation or ecological area in question was established."[51]

Mexican stocks imported into different parts of the South thus took on different characteristics -- presumably due to different origins, but also due to breeding to fit local environmental conditions. The first Texas stormproof variety of note was called Supak or Bohemian in honor of the German immigrant who developed the variety around 1860. Probable derivatives of this variety were Meyer and Texas Stormproof. These three varieties gained wide acceptance in Texas, and Texas Stormproof was distributed extensively across the South. In addition, these varieties provided the germplasm for breeders such as W. L. Boykin and A. D. Mebane who developed improved western big boll lines. In 1869, Boykin commenced a decade-long program of carefully selecting Meyer seed from the best plants on his farm near Terrill, Texas. Around 1880 he began planting his improved Meyer amongst Moon, a long staple variety, in a quest for a favorable hybrid. To breed storm resistant cotton, Boykin attached a string with a one pound weight to the tip of the locks and then held up the boll by the slender stock holding the fruit. He only selected seeds from bolls with stocks that didn't break under the pressure. Boykin's cotton was similar in appearance to Meyer, easy to pick, and exceptionally storm resistant. It had a high seed-to-lint ratio with a lint length of greater than one inch.

Mebane began studying cotton near Lockhart, Texas in the mid-1870s. Over the next quarter century he bred cotton in pursuit of a number of characteristics, including storm and drought resistance, higher lint ratios and yields, and larger easy-to-pick bolls. He succeeded in most of these areas and in the process changed his cotton's appearance, creating a stocky and compact plant that would not whip around in the wind. The high cotton so prized in the Mississippi Delta was a detriment in the windswept plains. When the boll weevil entered Texas, Mebane's variety became especially important because it was early to mature. Its success in weevil-infested areas led Seaman A. Knapp to name it

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[51] Ware, "Origin," p. 83.

"Triumph." Breeders created many other western big boll varieties in the pre-World War II era. Much of this effort focused on satisfying the critical need for early varieties.[52]

Over the late-nineteenth century, cotton production moved west by less than wheat or corn. Table 4 displays the changing geographic center of cotton production from 1839 to 1929. Cotton culture, which at its inception in the US in the 1790s was concentrated along the South Carolina and Georgia coast, had moved rapidly west over the antebellum period. By 1839, the mean center was in central Alabama. By 1859 it crossed the Mississippi-Alabama border. It was not until the 1880s that the center of wheat production was west of this longitude. But over the entire period from 1859 to 1919, the geographic center of cotton production remained within the boundaries of the state of Mississippi. Production did grow. As with corn, cotton production in the 1920s was also about 7 times greater than the crop in 1839.

The early twentieth century was a challenging period for cotton producers. The boll weevil, which entered the country around 1892, spread across the traditional Cotton South as a "wave of evil."[53] The pest invasion caused a wholesale transition in the traditional cotton belt to earlier maturing cottons. Among the additional consequences were the push of cotton culture onto the High Plains of the Texas and Oklahoma and the introduction of the crop into the Southwest (New Mexico, Arizona, and California). These environments were far drier and hotter than those found in the humid South. In the Southwest, sustained cotton production required irrigation, so a major adaption to new climatic conditions involved diverting rivers, drilling wells, and the construction of dams, canals, and ditches.

The responses to these new challenges are evident in Table 4 – in the increase in the miles of movement—and especially in the panels of Figure 8. This Figure displays the changing distribution of cotton production by location and climatic conditions from 1839 to 2002. The quantile lines for the tail of the distribution well display the shifts after 1910 of a significant fraction of production to more western lands, with hotter annual and July temperatures, lower precipitation, and higher elevations. The changes in the median are less dramatic. But those of the fringe, in the tails of the distribution, show

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[52] See Olmstead and Rhode, *Creating Abundance*. Ch. 4-5.

[53] Fabian Lange, Alan L. Olmstead, and Paul W. Rhode, "The Impact of the Boll Weevil, 1892-1932," *Journal of Economic History*, 69:3 (Sept. 2009), pp. 685-718.

what was possible. The swings could be quite dramatic. In the 1960s, 1970s, 1980s, traditional cotton areas in the Southeast temporarily dropped out of production. And in the mid-1970s and the 1980s, output in California doubled. The effects of such changes are evident in the figures.

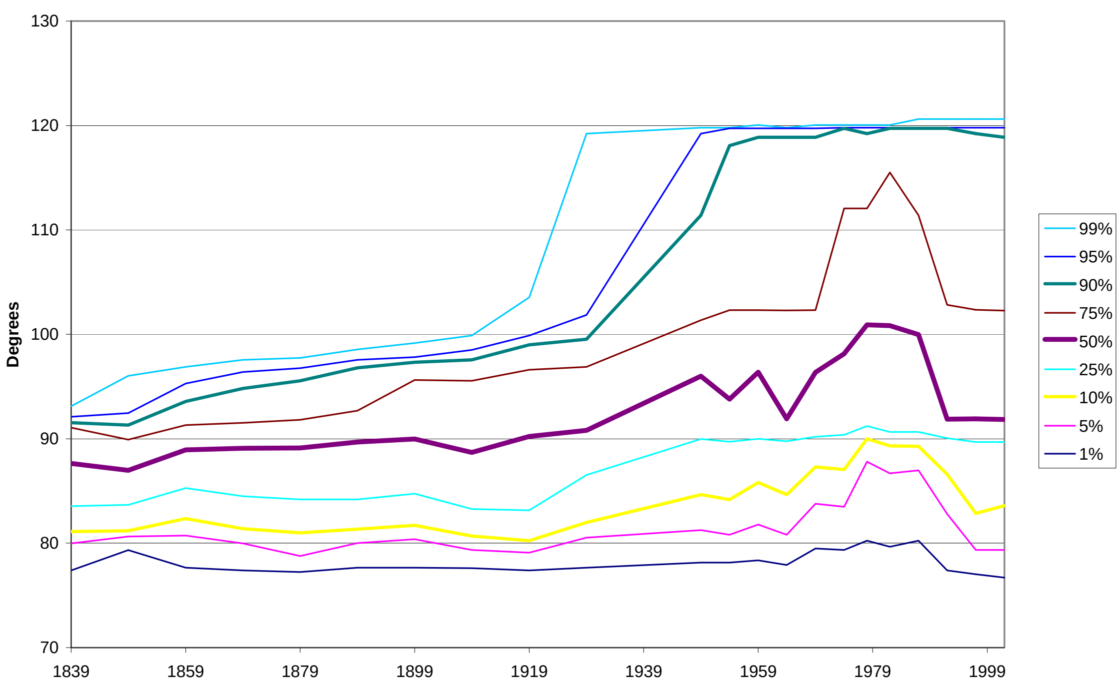
Table 4: Geographic Center of U.S. Cotton Production, 1839-1929

	North Latitude			West Longitude			Miles of Movement			
	deg	min	sec	deg	min	sec				
1839	32	52	55	87	5	2	1839	-	1849	33
1849	33	13	47	86	41	15	1849	-	1859	99
1859	32	57	12	88	21	41	1859	-	1869	8
1869	33	3	8	88	17	35	1869	-	1879	22
1879	33	21	47	88	14	59	1879	-	1889	44
1889	32	58	46	88	51	57	1889	-	1899	50
1899	32	55	19	89	43	55	1899	-	1909	58
1909	33	15	17	88	48	27	1909	-	1919	66
1919	33	35	50	89	52	24	1919	-	1929	104
1929	33	26	54	91	40	57	1839	-	1929	267

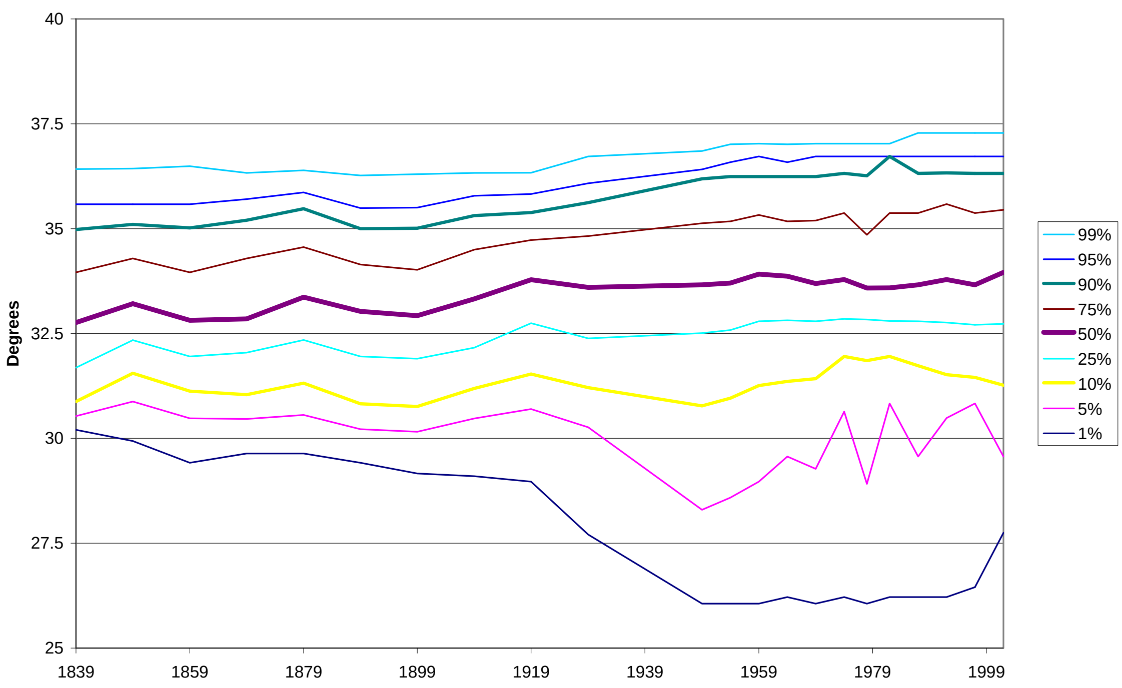
Source: See Table 1.

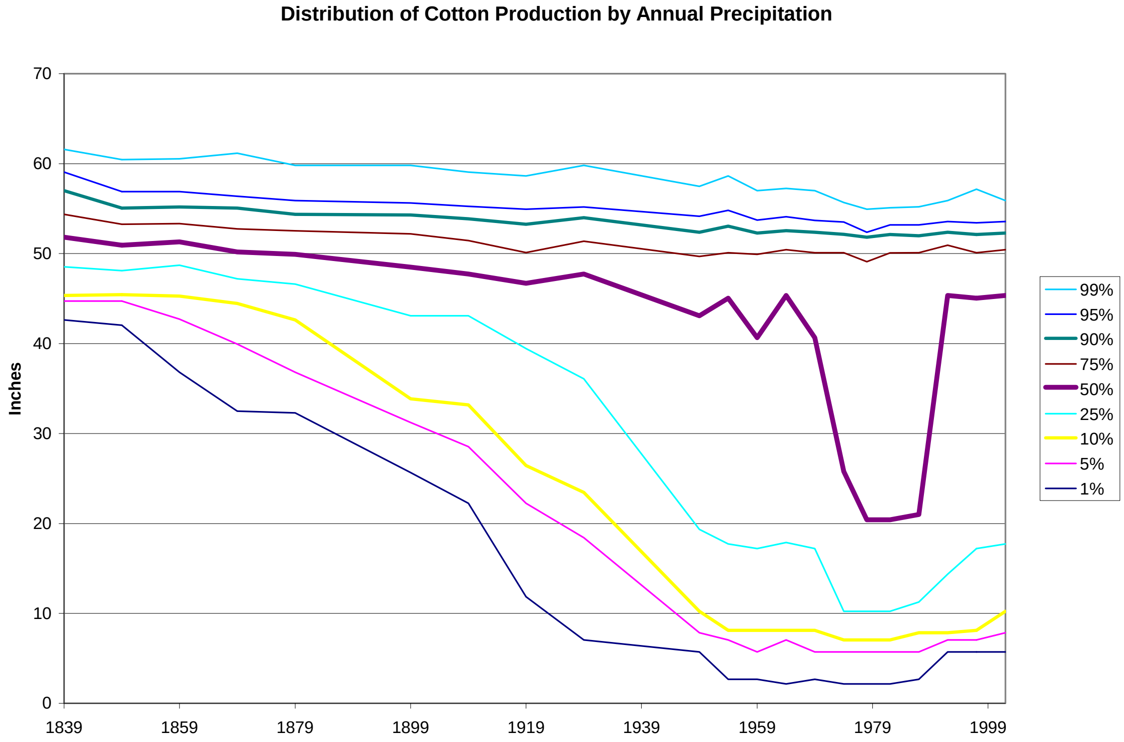
Figure 8: Distribution of U.S. Cotton Production, 1839-2002

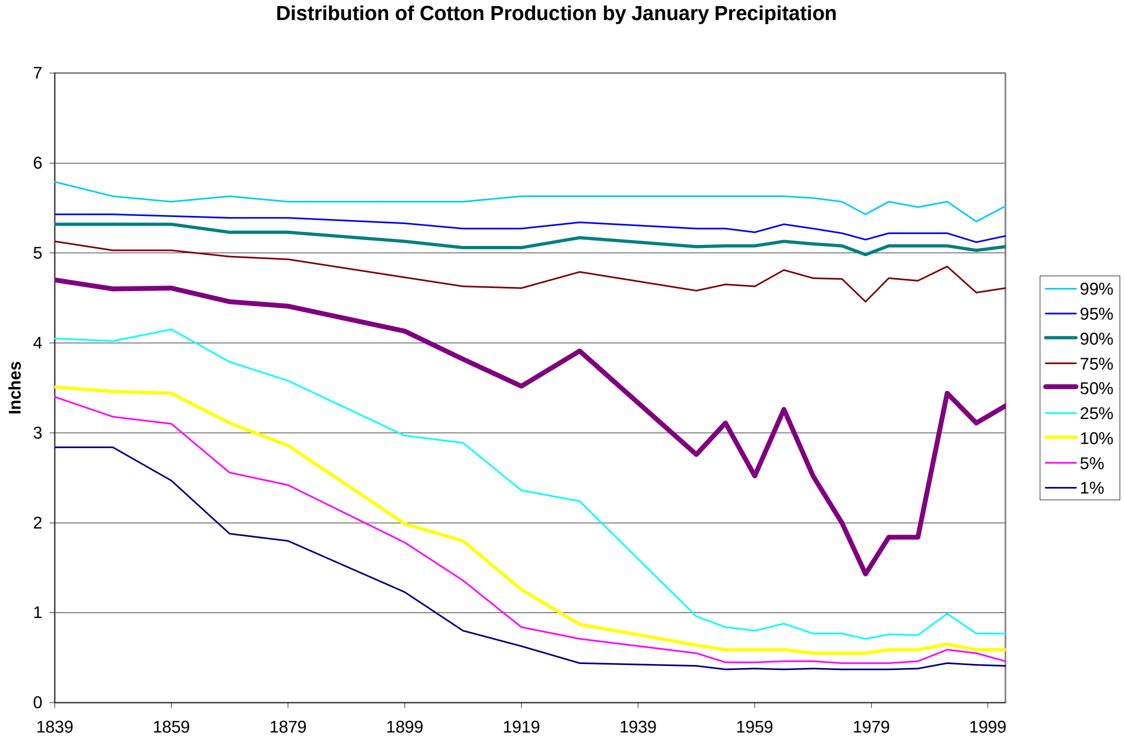
Distribution of Cotton Production by Longitude



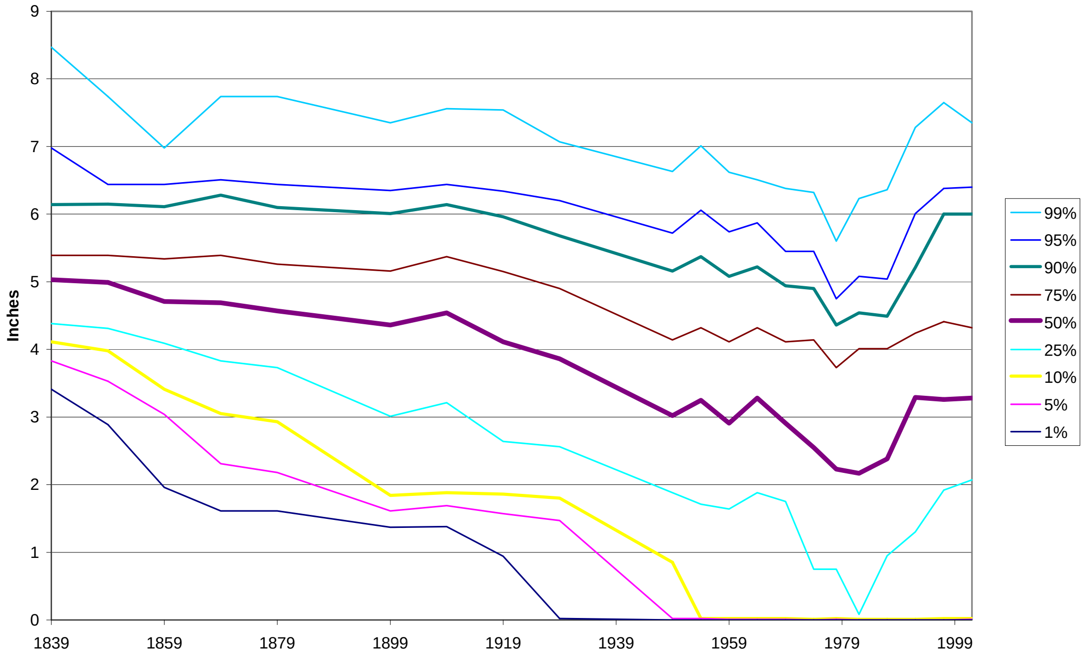
Distribution of Cotton Production by Latitude



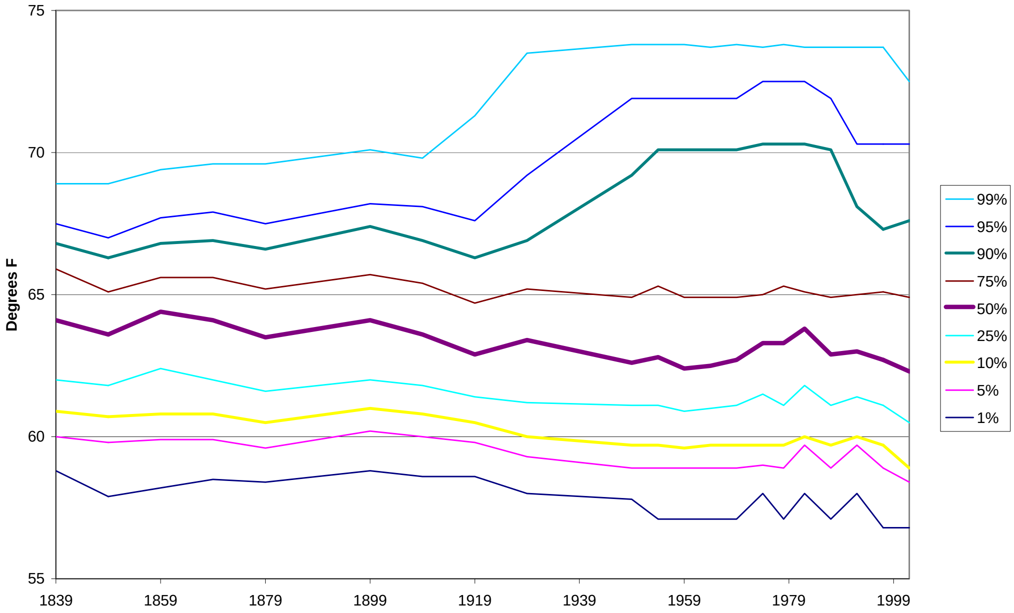

Distribution of Cotton Production by Annual Precipitation


Distribution of Cotton Production by January Precipitation

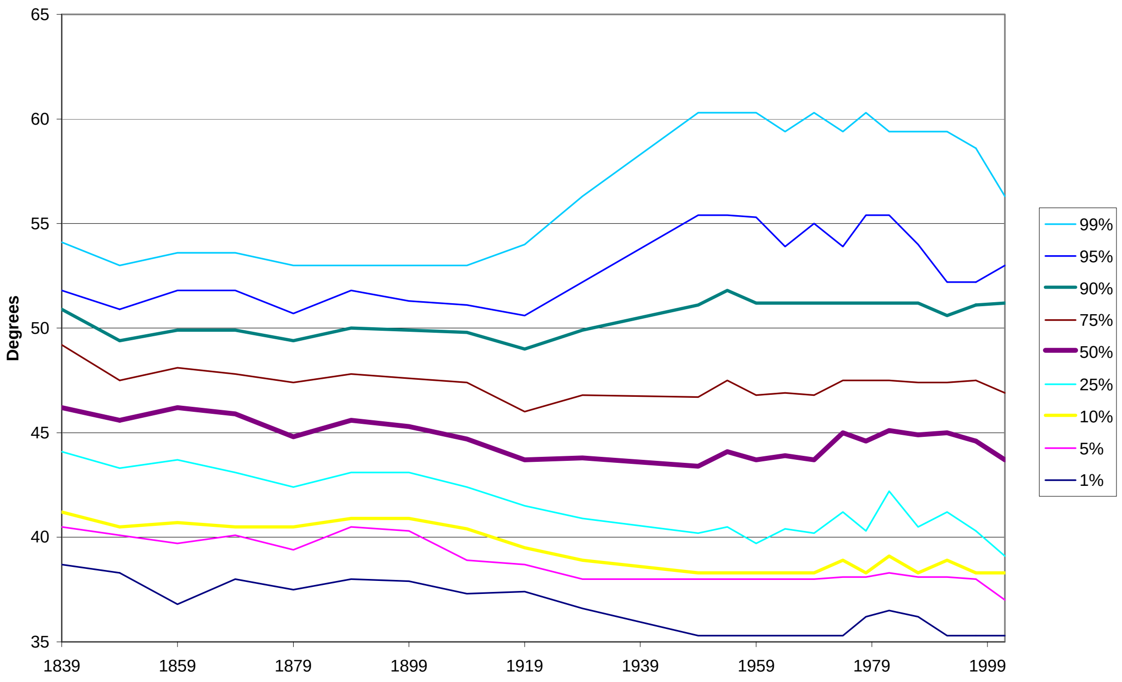
Distribution of Cotton Production by July Precipitation



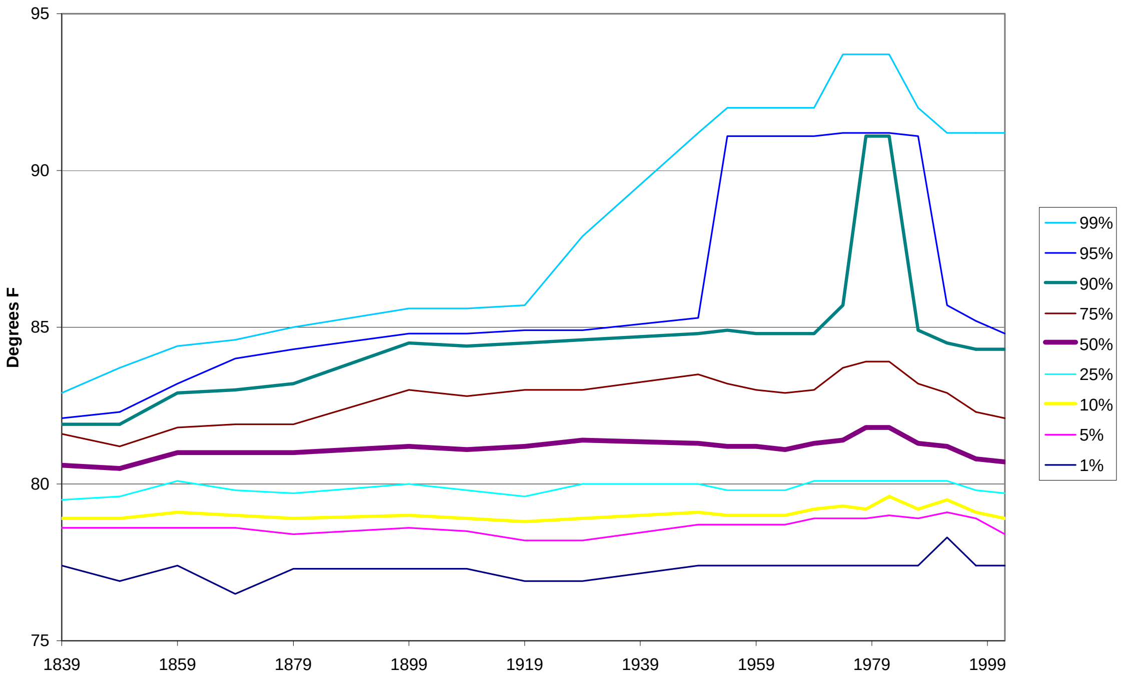
Distribution of Cotton Production by Annual Temperature

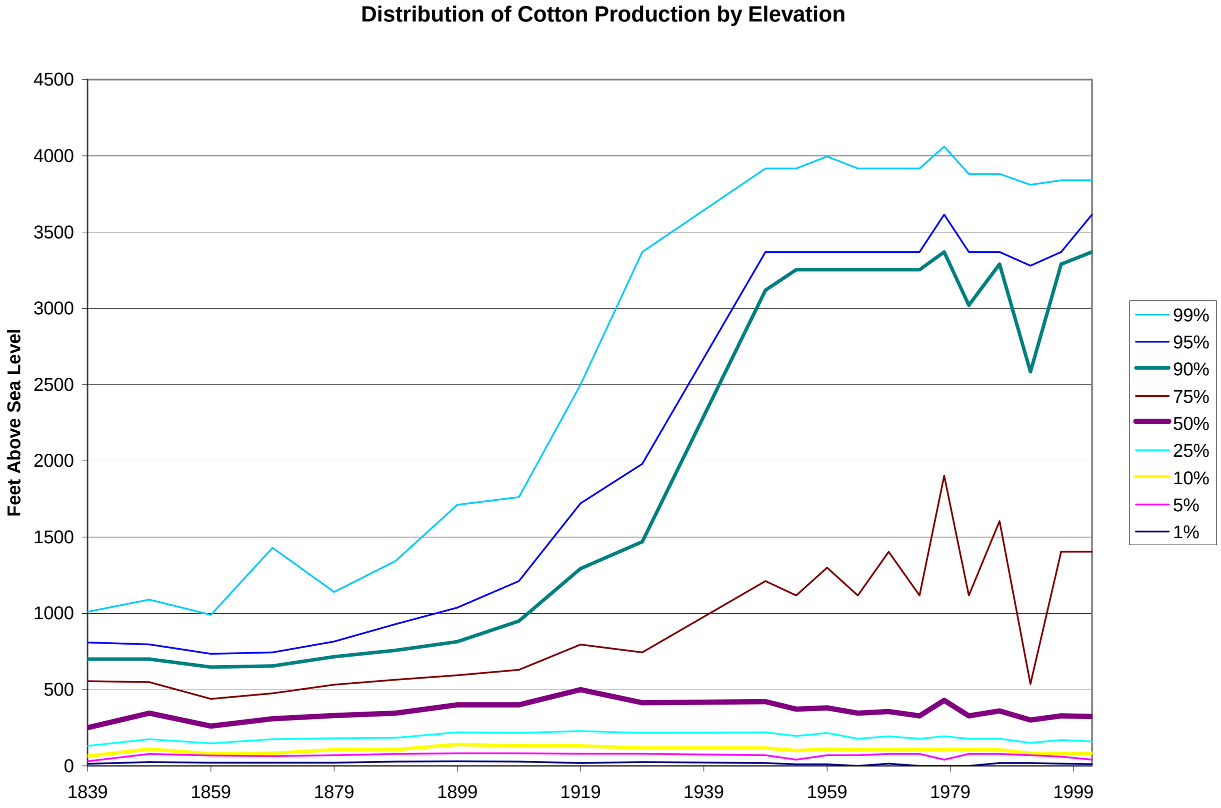


Distribution of Cotton Production by January Temperature



Distribution of Cotton Production by July Temperature



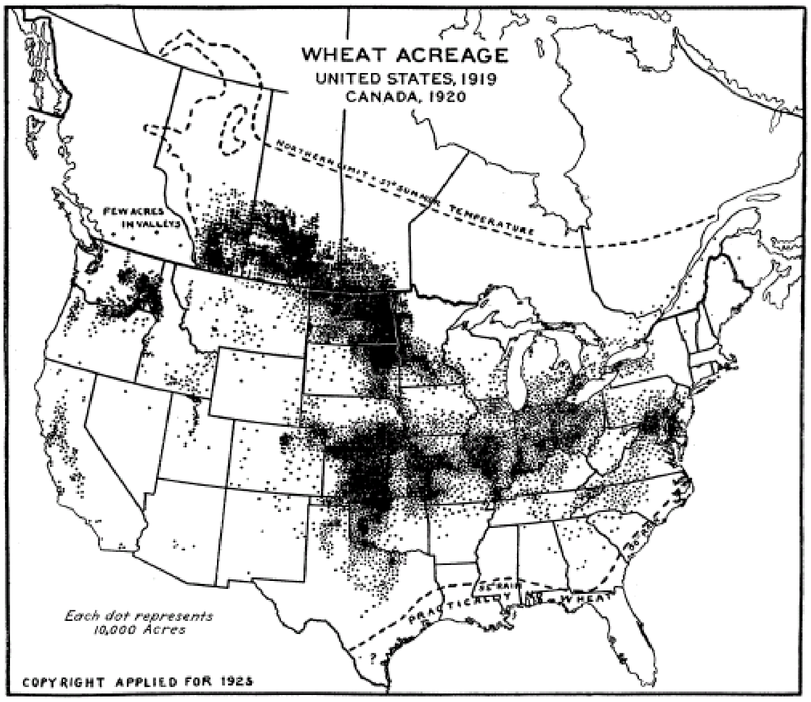


CONCLUSION

This paper seeks to provide historical perspective concerning future human responses to climatic variation. We document that during the nineteenth and twentieth centuries, new biological technologies allowed US farmers to push cultivation of the three major staple crops into environments previously thought too arid, too variable, and too harsh to farm. The climatic challenges that these farmers overcame often rivaled the climatic changes predicted for the next hundred years in North America. Our story would be strengthened if we integrated the agricultural histories of Mexico and Canada into this account largely based on the US experience.

It is important to make clear what this paper does not do. The predicted dire consequences to agriculture of global warming include the depletion of already stressed aquifers, a worsening of insect and disease problems, an increase in wildfires, and possible atmospheric changes that will adversely affect crops. Our research does not bear directly on any of these important issues. But the historical record does clearly show that farmers were able to develop technologies to push crop production into areas previously thought unsuitable for agriculture because the harsh climatic conditions. There is little reason to think that future technological advances and crop substitutions will not partially offset some of the problems created by global warming.

APPENDIX: Considering Canada and the US together



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.

The results of the CIMMYT research are more complex than the summary account from the BBC's Figure 1 suggest. Here is the study's own map:

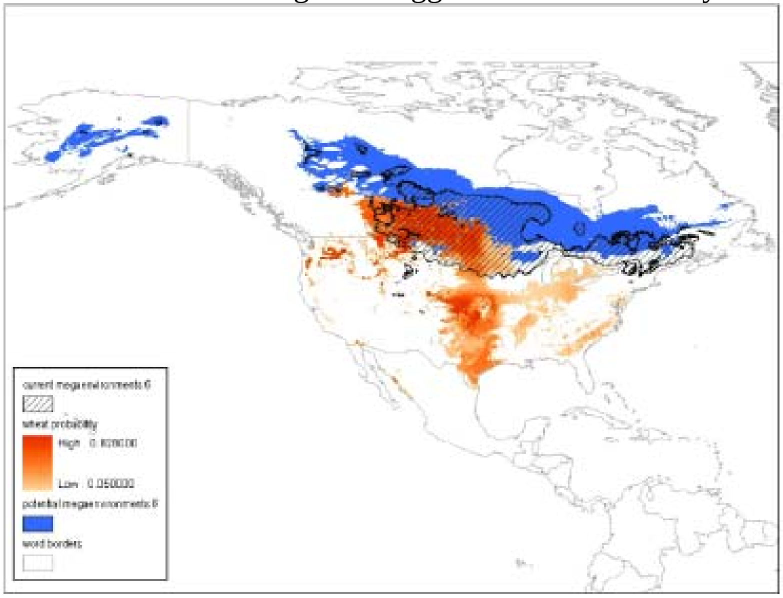
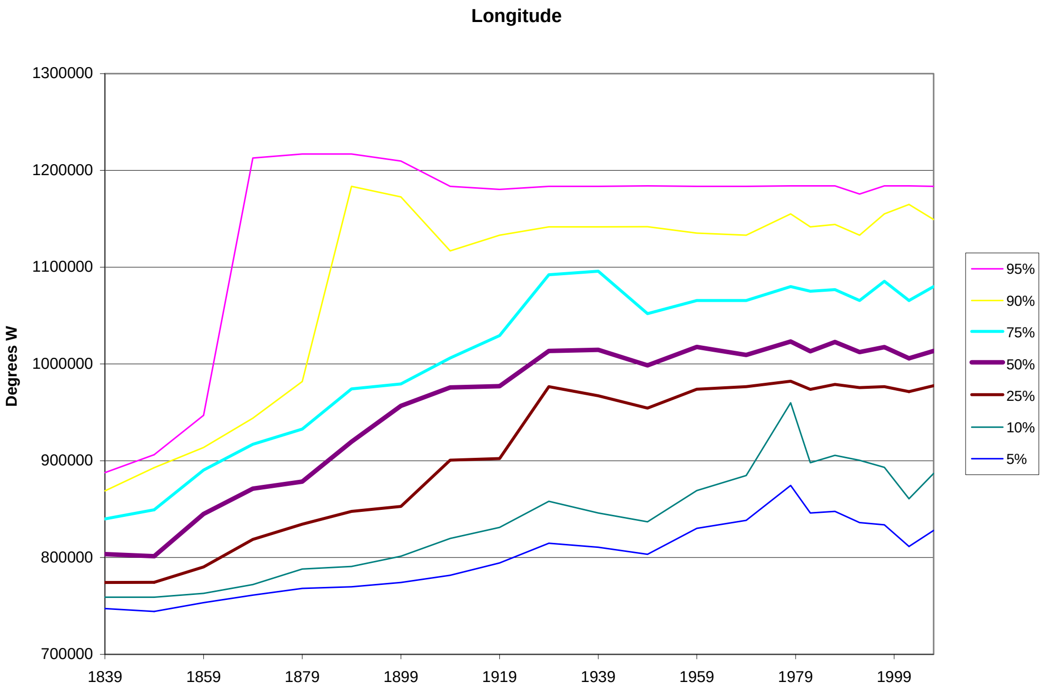


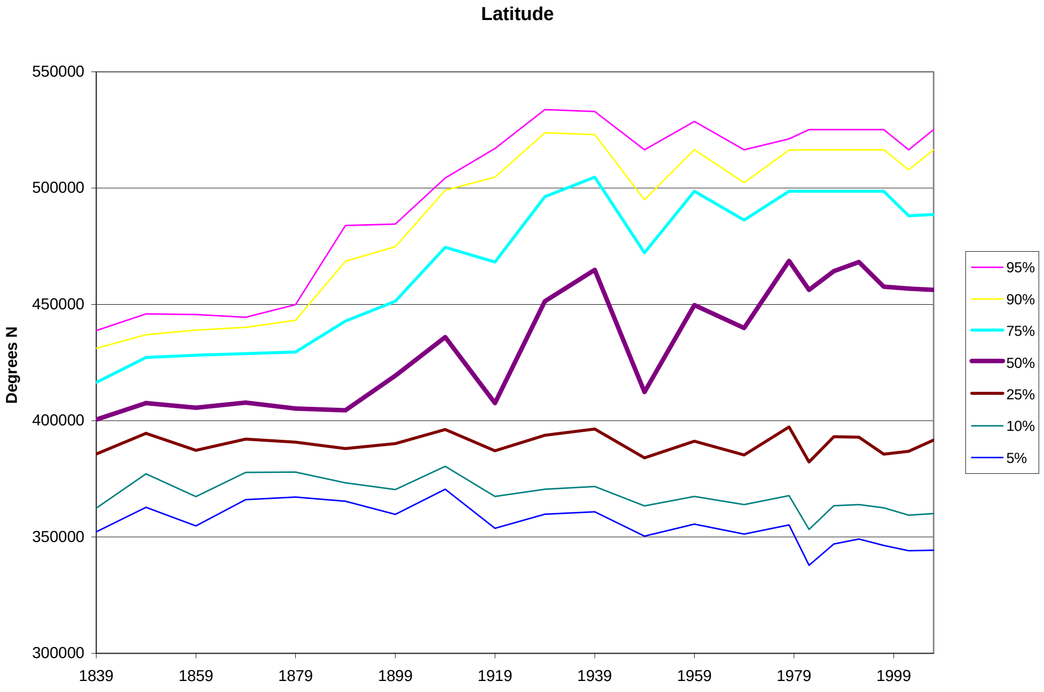
Fig. 4. Global warming and potential northward expansion of wheat mega-environment 6 in North America (2050).

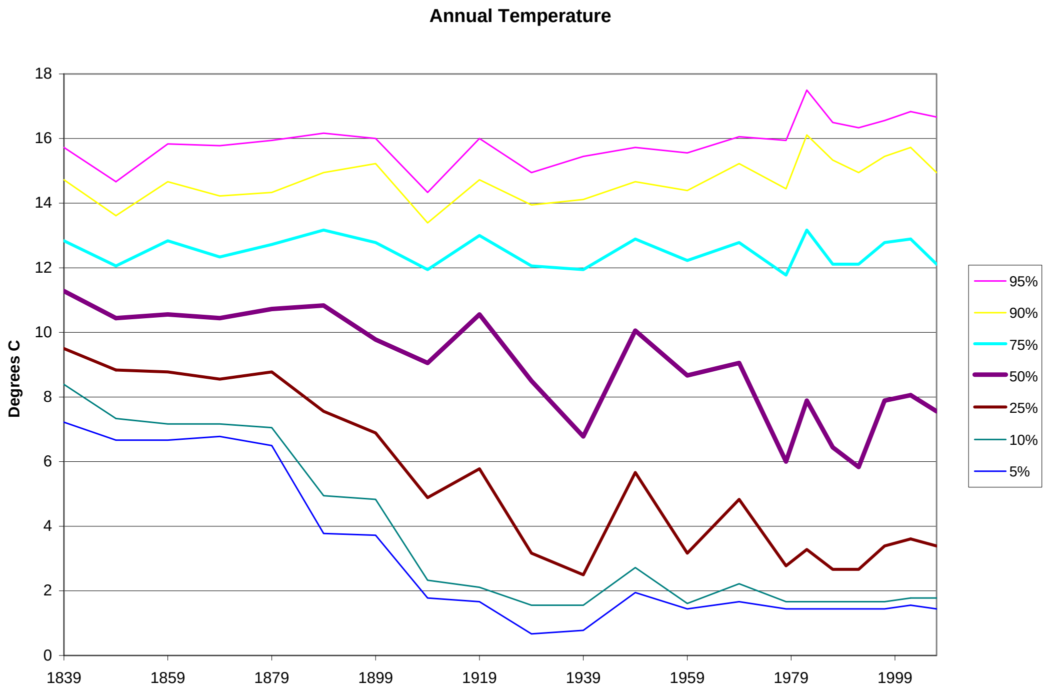
Source: Rodomirio Ortiz, Kenneth D. Sayre, Bram Vovaerts, Raj Gupta, G. V. Subbarao, Tomohiro Ban, David Hodson, John M. Dixon, J. Ivan Ortiz-Monasterio, and Matthew Reynolds, "Climate change: Can wheat beat the heat?." *Agriculture, Ecosystems and Environment* 126 (2008): 46-58. Map is on p. 52.

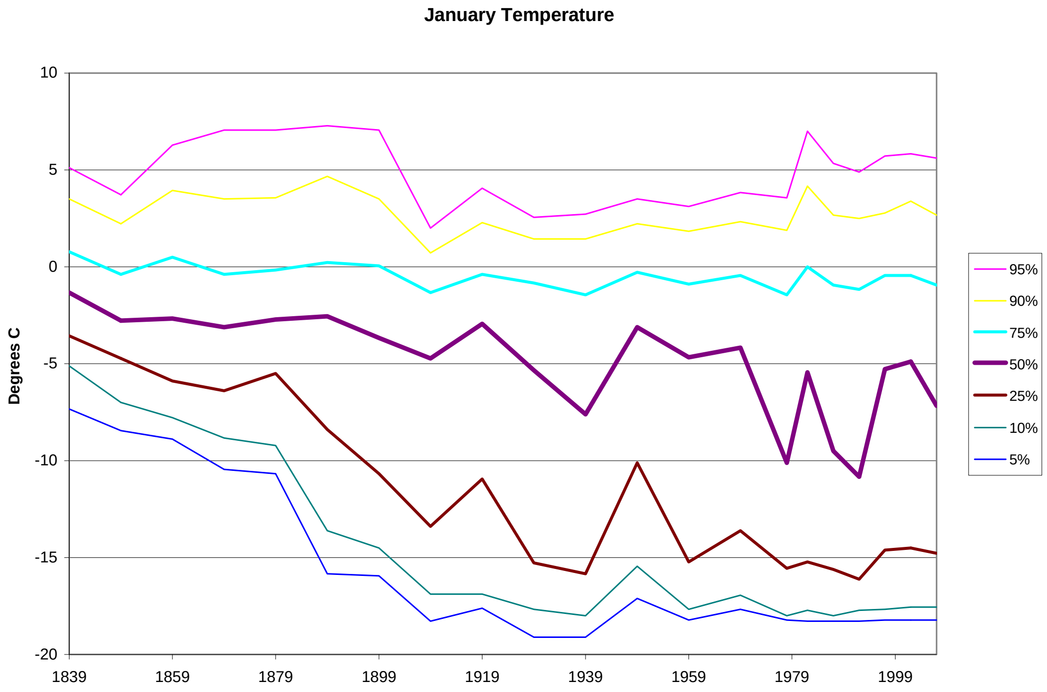
Four notes: (a.) the areas in dark orange are areas producing now that are considered likely to continue producing in 2050 (contrary to what is indicated in the BBC map); (b.) the areas in light orange are areas producing now that are considered likely to drop out by 2050; (c.) the areas in blue are areas not producing now that may enter viability for production by 2050; (d) many areas labeled in the BBC map as "viable for wheat now" but not "viable for wheat 2050" do not currently produce significant qualities of wheat.

Appendix Figures: Changing Distribution of US and Canadian Wheat

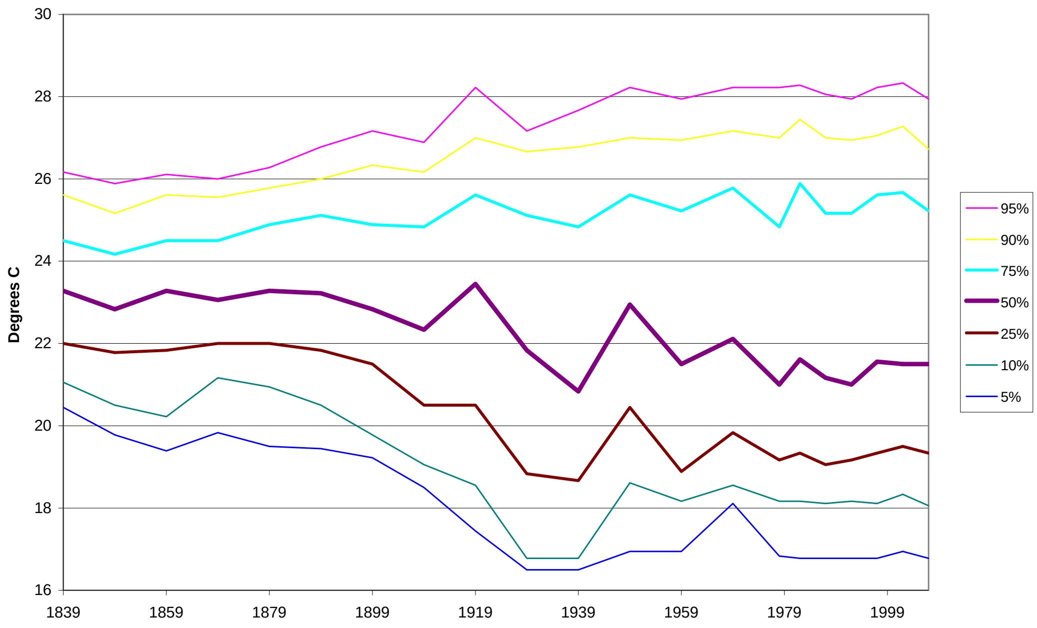




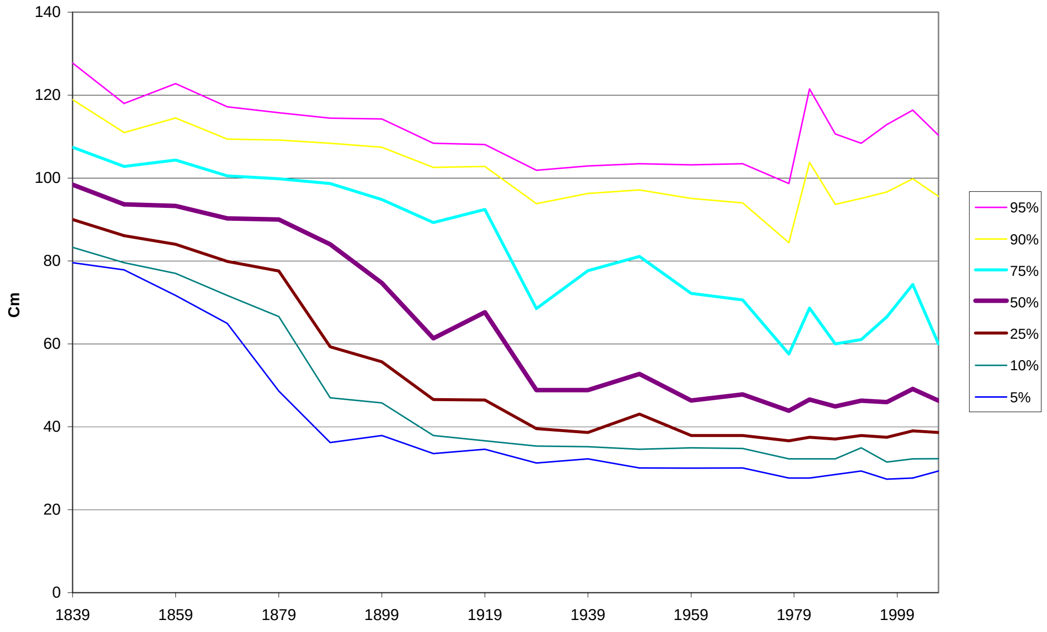

Annual Temperature
Degrees C
18
16
14
12
10
8
6
4
2
0
1839
1859
1879
1899
1919
1939
1959
1979
1999
95%
90%
75%
50%
25%
10%
5%

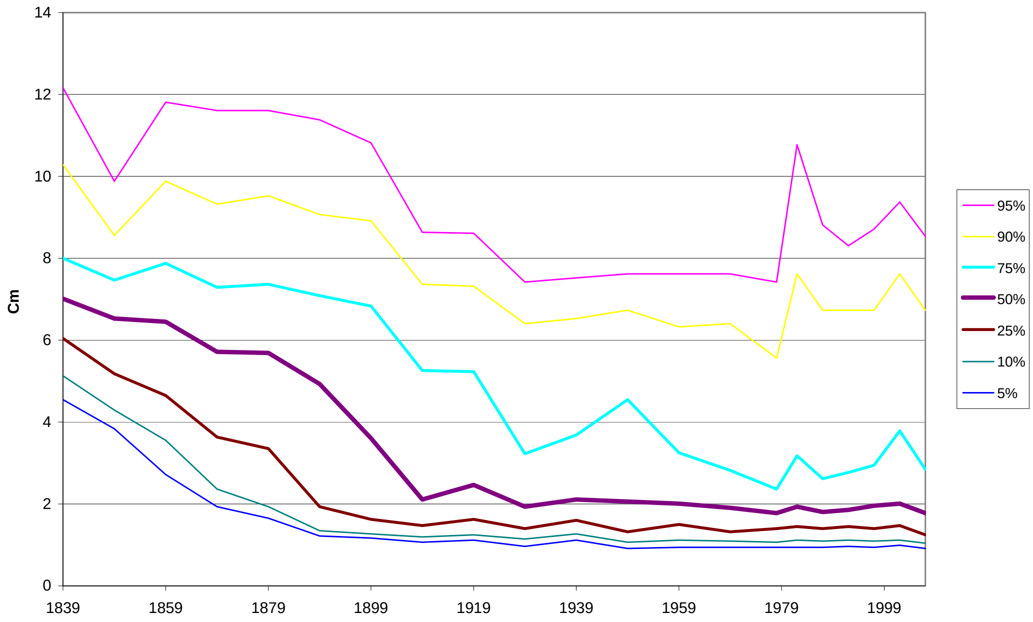

January Temperature
Degrees C
10
5
0
-5
-10
-15
-20
1839
1859
1879
1899
1919
1939
1959
1979
1999
95%
90%
75%
50%
25%
10%
5%

July Temperature

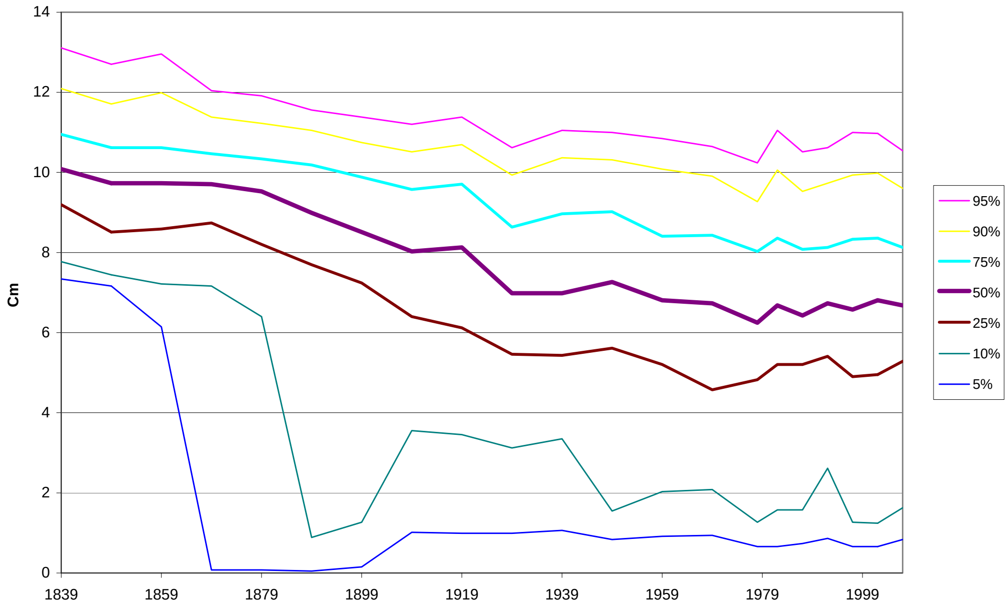


Annual Precipitation

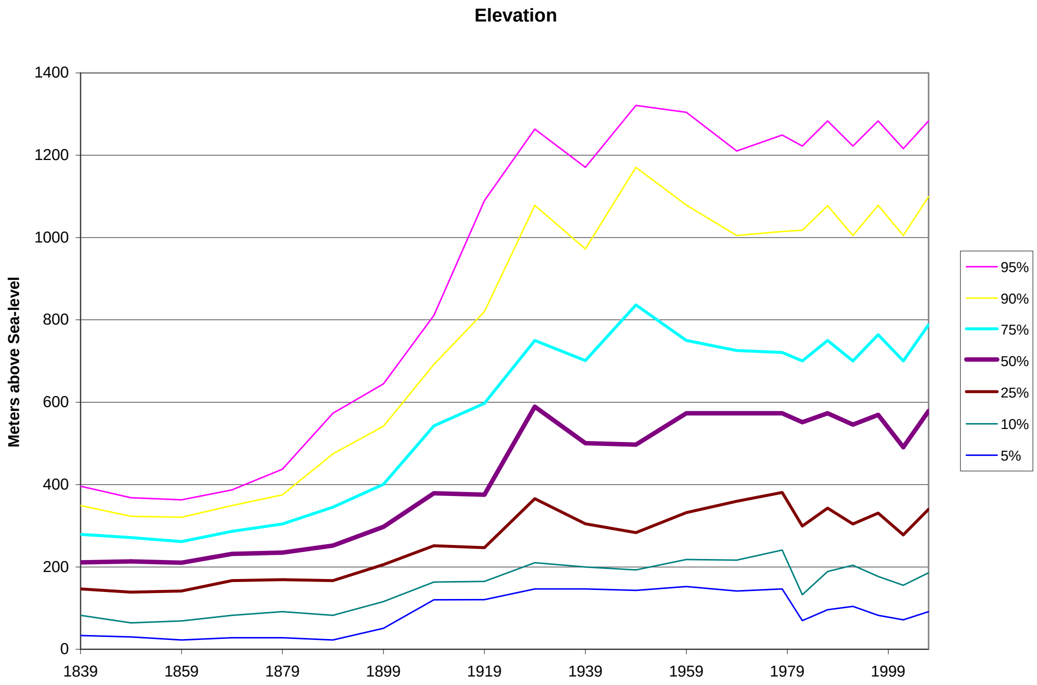




January Precipitation



July Precipitation


Elevation
Meters above Sea-level
1400
1200
1000
800
600
400
200
0
1839
1859
1879
1899
1919
1939
1959
1979
1999
95%
90%
75%
50%
25%
10%
5%