Adapting to Climate:
The Transformation of North American Wheat Production 1839-2009

Alan L. Olmstead and Paul W. Rhode

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Abstract:
The historical record offers considerable insight into the adaptability agriculture to climatic challenges. During the nineteenth and twentieth centuries, new biological technologies allowed North American farmers to push wheat production into environments previously considered too arid, too variable, and too harsh to cultivate. The climatic challenges that previous generations of farmers overcame rivaled the magnitude of those predicted for the next hundred years in North America.

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Alan L. Olmstead is Distinguished Research Professor of Economics and member of the Giannini Foundation of Agricultural Economics, University of California, Davis. Paul W. Rhode is Professor of Economics, University of Michigan and Research Associate at the National Bureau of Economic Research.

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 4-6 degrees F (2-3 degrees C) higher at is 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 the margin of cultivation northward 600-700 miles, about 10 degrees latitude, from the current limit of production. But as Figure 1 suggests, wheat likely 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 on the figure), but much will remain (the dark orange.)[3]

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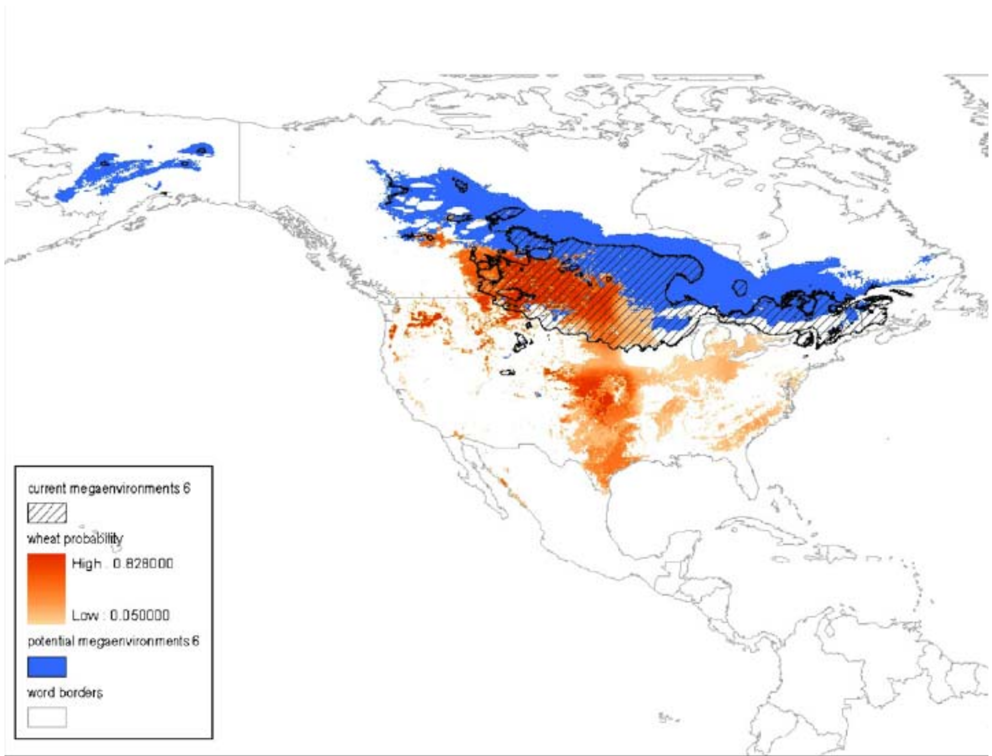
[1] David Fahrenthold, "Climate Change Brings Risk of More Extinctions," *Washington Post*, Sept. 17, 2007; p. A07; Intergovernmental Panel on Climate Change, "Summary for Policymakers," in S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor, and H. L. Miller, (eds,) *Climate 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. More recent research suggests that the climate changes may be roughly twice those projected by the IPCC. A. P. Sokolov, P. H. Stone, C. E. Forest, R. Prinn, M. C. Sarofim, M. Webster, S. Paltsev, C. A. Schlosser, D. Kicklighter, S. Dutkiewicz, J. Reilly, C. Wang, B. Felzer, J. M. Melillo, and H. D. Jacoby, "Probabilistic Forecast for Twenty-First-Century Climate Based on Uncertainties in Emissions (Without Policy) and Climate Parameters ," *Journal of Climate* 22: 19 (October 2009), pp. 5175–5204.

[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] Rodomiro Ortiz, Kenneth D. Sayre, Bram Govaerts, et al., "Climate Change: Can Wheat Beat the Heat?" *Agriculture, Ecosystems and Environment*, 126 (2008), 46-58; Rick Weiss, "Facing a Threat to Farming and Food Supply," *Washington Post*, Nov. 19, 2007, p. A06. The areas in dark orange are areas producing now that are considered likely to continue producing in 2050; the areas in light orange areas producing now

Figure 1: Projected North American Wheat Domain



Source: Rodomiro Ortiz, Kenneth D. Sayre, Bram Govaerts, 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.

The settlement of the North American Continent represented a grand natural experiment in biological adaptation as farmers repeatedly harmonized production practices with local climatic and soil conditions. This paper draws on this experience. We build a long-run production record to quantify and decipher how American and Canadian wheat farmers learned to produce in unfamiliar and hostile environments as the locus of production shifted westward. We do not examine the responses to climatic fluctuations over time at a set of fixed locations—over the entire span of wheat

that are considered likely to drop out by 2050; the areas in blue are areas not producing now that may enter viability for production by 2050.

cultivation in North America the sustained variations in climatic conditions at fixed locations were not extreme enough to offer much guidance. However, the absolute value of the cross-sectional changes in growing conditions that settlers encountered rivaled the magnitude of the predicted changes over the next century. The most of the agricultural changes associated with settlement occurred before an understanding of plant genetics when agronomy was still in the dark ages.[4]

Cross Sectional Changes in Production and Climate

Between 1839 and 1929, North American wheat output increased about 13 times. U.S production increased nearly 10 times rising from roughly 85 million in 1839 to 801 million bushels in 1929. By comparison, Canadian output increased over 100 times over these decades, soaring from roughly 4 million to 443 million bushels.[5] The rapid growth in output was crucially dependent on the western and northern expansion of cultivation. These geographic shifts are illustrated in Table 1, which shows the changing geographic center of production of North American wheat output from 1839 to 1929.[6] In 1839, the center was located Ohio about 10 miles southwest of Wheeling, (West) Virginia. Cultivation was concentrated in Ohio and upstate New York; relatively little was grown as far west as Illinois. Roughly three-fourths of Canadian production was in Ontario. By 1929, the center of North American production had moved 1,117 miles to west central South Dakota about 75 miles northeast of Rapid City.

Table 1: Geographic Center of North American Wheat Production, 1839-1929

Mean Location	Latitude Deg North	Longitude Deg West	Miles of Movement			
1839	39.93	80.80	1839	-	1849	70

[4] For an extended treatment of these issues for other crops see Alan L. Olmstead and Paul W. Rhode, *Creating Abundance: Biological Innovation and American Agricultural Development* (New York: Cambridge Univ. Press, 2008).
[5] The 1839 estimate of Canadian output is a crude indicator, based on partial data from nearby years. Specifically, in 1842 Upper Canada (Ontario) recorded about 3.2 million bushels, and in 1844 Lower Canada (Quebec) reported 843 thousand bushels. Evidence for Nova Scotia (1827 and 1851), New Brunswick (1851), and Newfoundland and Prince Edward Island (1861) suggests that the output from these providences would not dramatically increase our estimate for 1839.
[6] We calculated the center from census county-level production data and the location of the county's population centroid. For Canada we use production for county and census districts to a fixed location with each county or district.

1849	40.81	81.42	1849 - 1859	191
1859	40.53	85.04	1859 - 1869	170
1869	40.84	88.25	1869 - 1879	88
1879	40.81	89.94	1879 - 1889	180
1889	41.44	93.29	1889 - 1899	72
1899	42.06	94.41	1899 - 1909	153
1909	43.45	96.63	1909 - 1919	89
1919	42.47	97.56	1919 - 1929	256
1929	44.57	101.77	Total 1839-1929	1117

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 2,896 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*. Canadian data are from Agriculture volumes in the Census of Canada, treating 1851 as 1850 and so on.

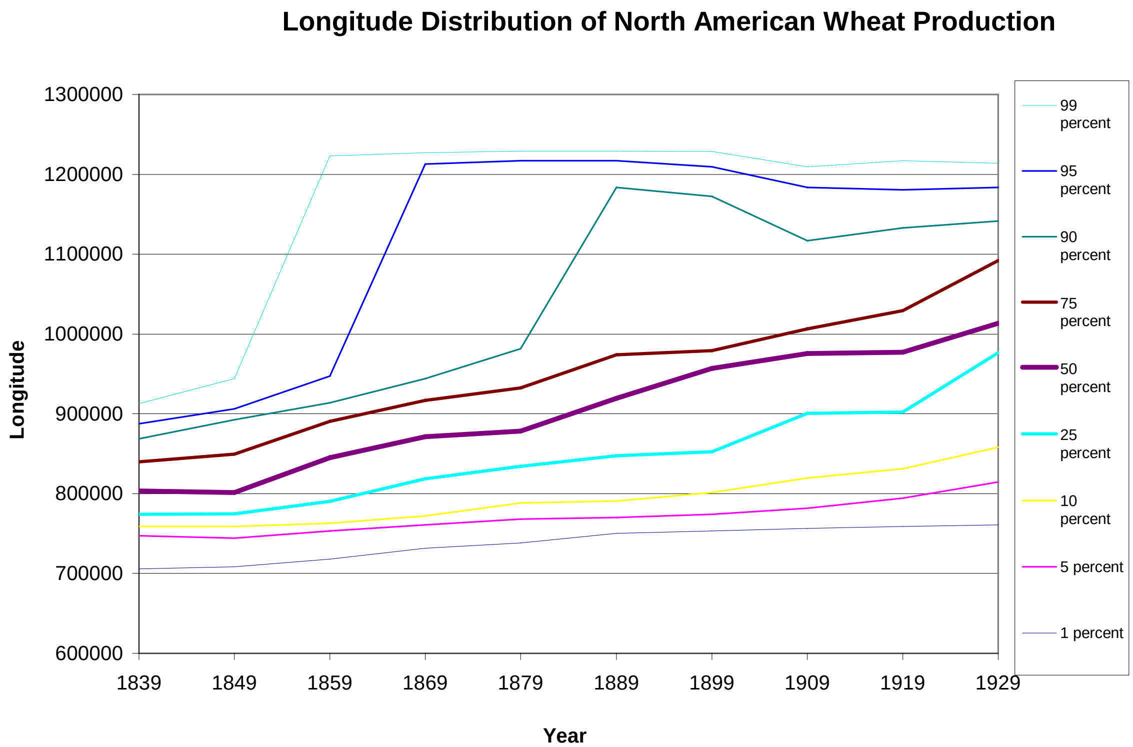
But even more impressive than these changes in geographic center of wheat production were the shifts in the range of conditions where the crop was grown. According to Mark Alfred Carleton, a prominent USDA agronomist, the regions of North America producing wheat in the early twentieth century were as "different from each other as though they lay in different continents" and required entirely different varieties of wheat.[7] The six panels of Figure 2 display the main features of the changing geographic distribution of the North American wheat crop across latitudes, longitudes, annual mean temperature and precipitation, January mean temperature, and elevation. . The series cover the period from 1839 to 2002 and combine county- and census district-level production data from U.S. and Canadian Censuses. The geo-climatic variables reflect average conditions in each county or census district (for western Canada) recorded over the 1941-70 period by the U.S. National Oceanic and Atmospheric Administration and by the Canadian Atmospheric Environment Service.[8] These variables do not capture year-to-year changes in the weather, and they predate the more recent secular climate changes associated with the global warming.

[7] Mark Alfred Carleton, *The Basis for the Improvement of American Wheats*, USDA Division of Vegetable Physiology and Pathology *Bulletin*, no. 24 (1900), p. 9.
[8] ICSPR-No, 9075 Codebook, p. 96. The available series include mean temperature (Jan., July, Annual); annual mean precipitation (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." The Canadian data come from Atmospheric Environment Service, *Temperature and Precipitation, 1941-1970*, 6 vols. (Downsview, Ontario: Department of the Environment, 1972).

The panel showing the distribution of wheat production by longitude summarizes the 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 in California where farmers adopted novel techniques and varieties to cope with the hotter and more arid environment. The median latitude of production (Panel B) is relatively constant until the 1890s when production expanded in the northern plains and the Canadian prairies. In 1929 the median production took place at a latitude near the northern fringe of production in 1839 (the 99 percent line). The most northern 25 percent of production (reflected in the 75 percent line) moved roughly 8 degrees (over 500 miles) between 1839 and 1929. The most northern 10 percent of production moved even more.

Dramatic changes occurred in the distribution of production by annual precipitation. In 1929, median production took place on land with less than half the precipitation of the median production in 1839. The 1929 median production was in a drier environment than virtually anything recorded in 1839 or even 1849. It is important to note, that because total production increased roughly13 times between 1839 and 1929, the quantity of output captured in either the top and bottom 10 percent deciles of Table 1 exceeds the entire output in 1839. Thus in 1929 the marginal fringe with less than 14 inches of rain produced far more wheat than was grown in the United States and Canada in 1839. At that time little wheat was produced in areas with less than 30 inches of rain. The range of annual moisture conditions also widened substantially; the difference between the 10 and 90 percent lines went from 14 to 24 inches between 1839 and 1929.

The median annual and January temperatures fell by 5 degrees F and 7.2 degrees F respectively. The range of temperature conditions greatly widened, especially in colder domains. The 90-10 differential doubled from 11.5 to 22.3. Focusing on average annual temperature, the coldest 10 percent of production occurred at 47.1 degrees F. in 1839 but at 34.8 degrees in 1929, a change of 12.3 degrees. The coldest 10 percent of production measured by January temperature occurred at 22.8 degrees F. in 1839 but at 2.0 degrees in 1929, a fall of 20.8 degrees. In 1929 more wheat was grown in places where the January temperature was less than 2.0 degrees than was grown in North America in 1839—a date when little wheat was produced in areas with a January temperature as low as 13 degrees. The changes have not been limited to moving into places with colder winters, but the expansion in hot areas was swamped by the even greater shifts into cold areas. Between 1839 and 1929 the median elevation of production increased by 1200 feet and the upper decile (the 90 percent line) rose by almost 2400 feet. In no period did the areas currently threaten by rising sea levels produce more than a trivial fraction of North American wheat.



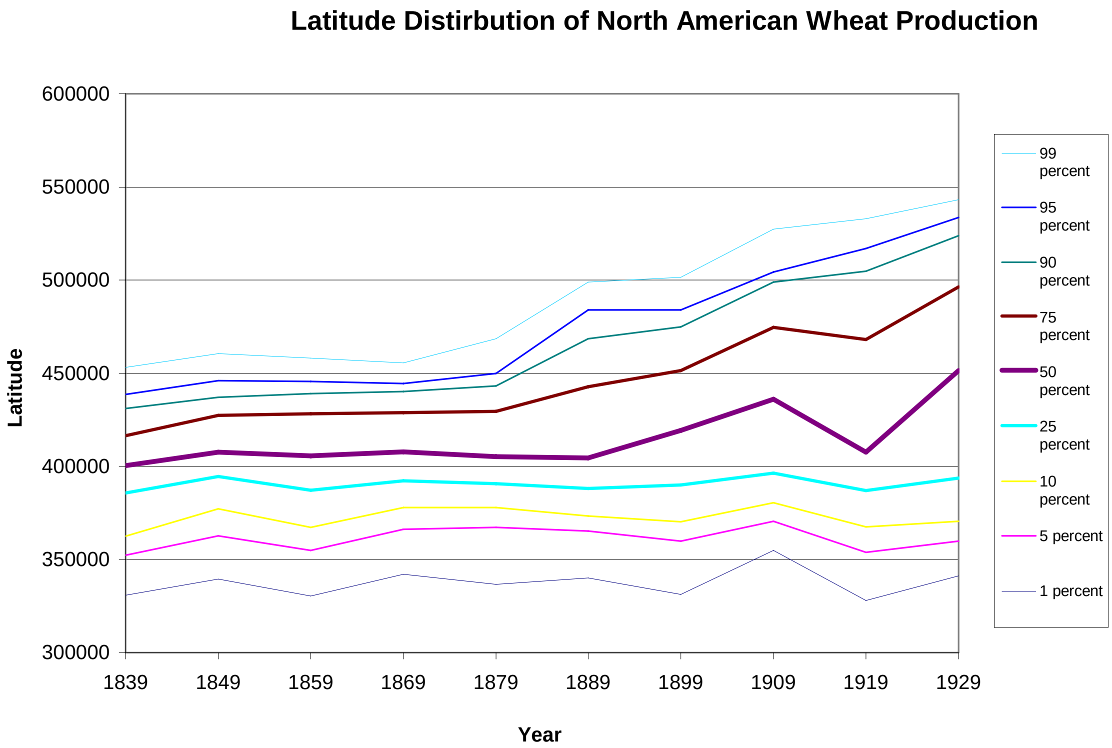
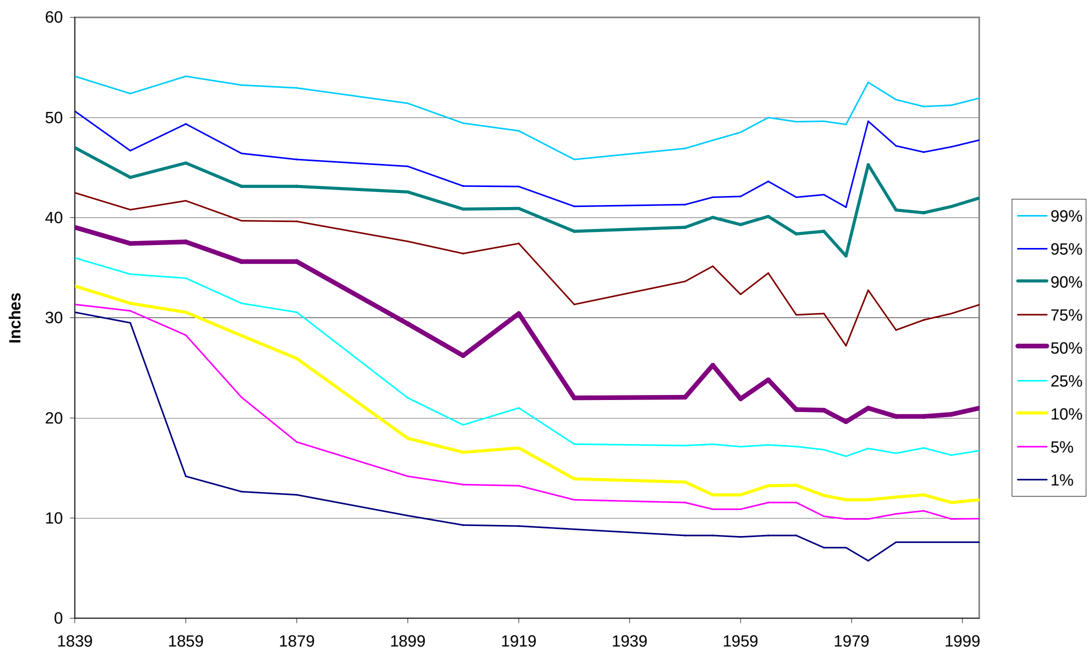
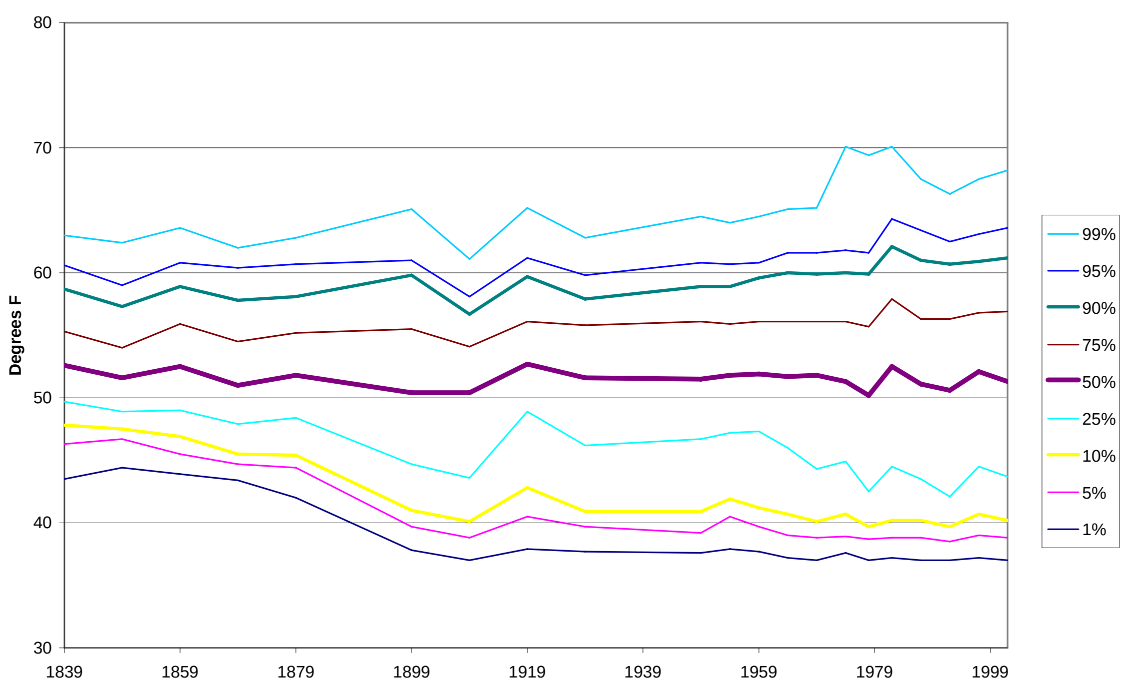


Figure 2: Distribution of U.S. Wheat Production, 1839-2002

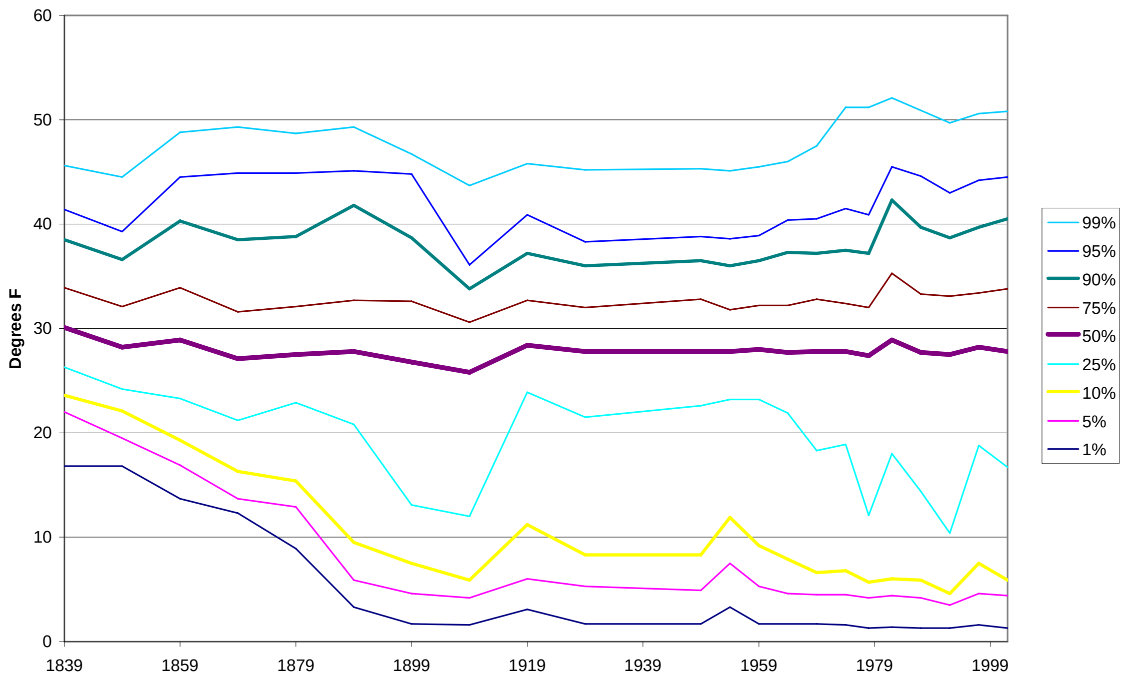
Distribution of Wheat Production by Annual Precipitation



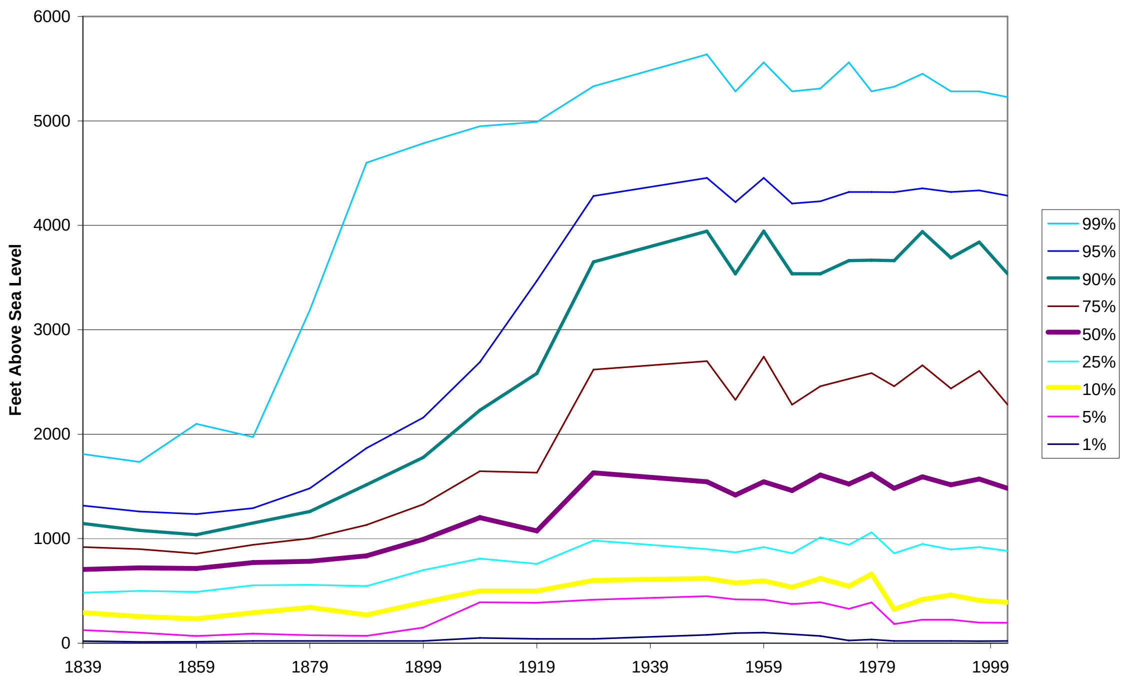
Distribution of Wheat Production by Annual Temperature



Distribution of Wheat Production by January Temperature



Distribution of Wheat Production by Elevation



Biological Innovation to Adapt to Environmental Change

The march of agriculture across the North American continent was first and foremost a story of farmers adapting to new agro-climatic challenges. Wheat cultivation was first introduced into the territory that would be come Canada and the United States in 1605 at the first French settlement at Port Royal in what is now Nova Scotia. Cultivation in eastern Canada expanded over the coming centuries, but generally suffered from diseases, insects, and the propensity of the soft white winter wheat to die from winterkill. Farmers tried a "succession of types or landraces," including Red Chaff, White Flint, Kentucky White Bearded, and Genesee White Flint, "in search of ones that would overcome some of the impediments to successful wheat production."[9] In New England, settlers were enacting a similar scenario—one that would be repeated thousands of times as farmers attempted to match crops to local conditions. The failure to find winter-hardy, rust resistant varieties largely explains why New England never emerged as an important wheat producing area. This failure was not for a lack of trying.[10] When pioneers 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. Attempts to grow traditional wheat varieties often ended in disaster.

The experiences of the early members in Selkirk colony who settled on the Red and Assiniboine Rivers near Lake Winnipeg offer an example. The winter wheat, first tried in 1811-12, failed. After the ground thawed, the fields were resown with spring wheat which, due to drought and cultural problems, also failed. In 1813-14, the colonists obtained a small amount of spring wheat seed from Fort Alexander, which yielded sufficient grain to continue cultivation. But in 1819, a locust plague completely devastated the crop, leaving the colony without seed. During the winter and early spring of 1820, a band of the settlers traveled 660 miles (each way) to Prairie du Chien on the upper Mississippi River to secure a replacement seed. After about a decade of hungry

[9] W. J. White, "Plant Breeding in Canada's Formative Years," in *Harvest of Gold: The History of Field Crop Breeding in Canada*, eds. A. E. Slinkard and D. R. Knott, Ch. 1 (Saskatoon: University Extension Press, University of Saskatchewan, 1995), esp. p. 6; and R. M. DePauw, G. R. Boughton, and D. R. Knott, "Hard Red Spring Wheat," in *Harvest of Gold*, Ch. 2; and Ron DePauw and Tony Hunt, "Canadian Wheat Pool," in *World Wheat Book*, 479-515.
[10] Olmstead and Rhode, *Creating Abundance*, p. 42.

times, the colony began to sustain itself, if not flourish.[11] The prolonged troubles of the Selkirk colonists represented a clear case of settlers leapfrogging beyond the limits of biological knowledge. But even when settlers inched west in a more orderly fashion the challenges of new climates were daunting. In the 1840s the repeated attempts to grow winter wheat on the Wisconsin prairie ended in failure and the crop only succeeded after farmers switched to a new variety of spring wheat.[12] Similar stories of disappointment were common as farmers learned to cope with different geo-climatic conditions.
Maps of the Great Plains from the 1820s to the 1870s often depicted the territory as the "Great American Desert."[13] The region "was long considered to be incapable of agricultural development."[14] 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 a decades long "experiment in agriculture on a vast scale."[15] In addition to individual farmers ; railroad, and federal and state officials significantly miscalculated the climatic obstacles that had to be overcome.[16] Success was often dependent on knowledge introduced by immigrants from frigid and arid locales of Eurasia. Just as there is uncertainty about future secular changes in weather patterns, 19th century settlers lacked reliable information about long run conditions.

The successful spread of wheat cultivation across the vast tracts extending from the Texas Panhandle into the Canadian prairies required the extension of railroads and

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

[12] 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, in Bulletin of the University of Wisconsin*, 101; *Economics and Political Science Series*, 1, no. 2, 67-214 (Madison, WI: 1904), pp. 125-26. We use the traditional term "variety" instead of the modern term "cultivar" to maintain consistency with the historical literature we cite.

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

[14] Carter Goodrich, et al., *Migration and Economic Opportunity: The Report of the Study of Population Redistribution* (Philadelphia: University of Pennsylvania Press, 1936), p. 207.

[15] 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.

[16] 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.

harvest mechanization. But it also 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. Mrs. Fife, who was the daughter of a farmer and seedsman, saved the precious seed stock from foraging cattle. 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 across the Canadian Shield into the Prairie Provinces.

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 from southern Russia, with the introduction of this strain in 1873.[17] Early settlers in Kansas had experimented with scores of soft winter varieties common to the eastern states.[18] 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."[19] The sharp fall in winterkill rates after the adoption of Turkey lends credence to this view.[20] In 1919, Turkey-type wheat made up over 80 percent of the wheat acreage in Nebraska and

[17] Turkey would play key role in the Green Revolution. It was imported into Japan from the United States around 1890 and would become a parent of Norin 10. L. P. Reitz and S. C. Salmon, "Origin, History and Use of Norin 10 Wheat, *Crop Science*, Vol. 8, Issue 6, 1968, p. 686-689. Carleton R. Ball, "The History of American Wheat Improvement," *Agricultural History* 4:2 (1930), entire article is pp.48-71; citation is from p. 63.

[18] James C. Malin, *Winter Wheat in the Golden Belt of Kansas* (Lawrence, KS: University of Kansas Press, 1944), pp. 96-101.

[19] 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.

[20] Malin, *Winter Wheat*, pp. 156-59; Salmon, Mathews, and Luekel, "Half Century of Wheat Improvement," pp. 6, 78-79 reports on the change in winterkill rates..

Kansas, and nearly 70 percent in Colorado and Oklahoma. It accounted for 30 percent of total U.S. wheat acreage and 99 percent of the nation's hard winter wheat acreage.[21]

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.[22] The general progression in varieties allowed the North American wheat belt to push over 1,100 miles northward and westward, and significantly reduced the risks of crop damage everywhere.[23]

In both the United States and Canada many varietal innovations were the direct result of government research. In 1886 Parliament created the Canadian federal experiment station system, with the Central Experimental Farm established in Ottawa and additional stations subsequently opened across the country. William Saunders began breeding work at Central Farm shortly after its inception. One of Saunders' early introductions was the Ladoga cultivar from northern (60° N) Russia in 1887. This wheat matured earlier than Red Fife, but yielded poorer quality flour. The value of earliness was reinforced by the virtual destruction of the western crop in 1888 by a very early autumn frost. William Saunders' more lasting contribution resulted from a systematic program of hybridizing early-maturing cultivars with high-quality cultivars. In 1903 his son, Charles Saunders, took over the work. 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.[24] Released in 1909, this famous cultivar matured about 10 days earlier than Red Fife and was more resistant to disease. These qualities led to its rapid adoption.

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[21] Karl S. Quisenberry, and L. P. Reitz, "Turkey Wheat: the Cornerstone of an Empire," *Agricultural History* 48:10 (1974): 98-114; Malin, *Winter Wheat.*

[22] 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).

[23] Unstead, "The Climatic Limits," pp. 347-366, and 421-41.

[24] The actual cross leading to Marquis was probably made in 1892. William Saunders led the effort and his sons, Arthur and Charles assisted. Elsie M. Pomeroy, *William Saunders and His Five Sons: The Story of the Marquis Wheat Family* (Toronto: Ryerson Press, 1956), 48-52; J. Allen Clark and B. B. Bayles, "The Classification of Wheat Varieties Grown in the United States," *USDA Technical Bulletin* 459 (1935): 69; Paul de Kruif, *Hunger Fighters* (New York: Harcourt, Brace and World, 1928), 4;. J. W. Morrison, "Marquis Wheat—A Triumph of Scientific Endeavour," *Agricultural History* 34, no. 4 (1960): 182-188.

By 1918 Marquis accounted for over 80 percent of western Canada's wheat.[25] 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.[26]

The spread of Marquis was not an isolated case. Following extensive expeditions to the Russian plains, Carleton introduced Kubanka and several other durum varieties in 1900.[27] These hardy spring wheats proved relatively rust resistant. By 1903 American durum production, which was concentrated in Minnesota and the Dakotas, approached 7 million bushels. By 1906, durum production soared to 50 million bushels.[28] At the time of the first reliable USDA survey of wheat varieties in 1919, North Dakota, South Dakota, and Minnesota farmers grew hard red spring and durum wheats to the virtual exclusion of all others. Carleton also left his imprint on winter wheat belt. 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.[29]

Decades of research showed that in 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."[30] In 1920, S. C. Salmon who later introduced dwarf wheat from Japan to the United States, concluded that without Turkey 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.[31]

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[25] Buller, p. 254.
[26] J. Allen Clark, John H. Martin, and Carleton R. Ball, "Classification of American Wheat Varieties," *USDA Bulletin*, no. 1074 (1922), p. 901.
[27] 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 State," *USDA Bulletin*, no. 1276 (1925), pp. 8-9.
[28] 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.
[29] Carleton, "Hard Wheats," pp. 404-8.
[30] 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. Vol. 5 (New York: Academic Press, 1953), p. 14.
[31] Salmon, "Developing Better Varieties," pp. 211-12. See fn 9, p. 27 in *Creating Abundance* for discussion of habit.

Wherever feasible, farmers prefer to grow winter wheat instead of spring wheat. Winter wheat generally offers higher yields and is less subject to damage from insects and diseases, but in colder climates it suffers high losses to winterkill. So in the upper Midwest, the northern Great Plains, and the Canadian prairies spring wheat was generally the only option. Agronomists have long recognized that the development of hearty winter varieties that could be grown in harsher climates was an historic achievement. Our local-level production data allow us quantify the impact of these fundamental biological innovations.[32]

Figure 3 maps the spring-winter wheat frontiers for 1869 and 1929. The two lines on the map plot estimates for each degree of longitude between 87º and 105º of the latitude where spring wheat output equaled winter wheat output in 1869 and 1929 for the main wheat-growing areas of the United States.[33] 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; 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 into northern Texas. By 1929, the spring-winter 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, winter wheat production crept northward across most of Kansas, Iowa, Nebraska, and Oklahoma as well as large regions of Illinois, Wisconsin, and Colorado. The area between the 1869 and 1929 spring-winter wheat frontiers accounted for almost 30 percent of U.S. wheat output in 1929, and nearly as much wheat was grown in the U.S. in 1869. This displacement of one wheat type by another represented an exceedingly important case of agricultural adaptation to climate. There were also

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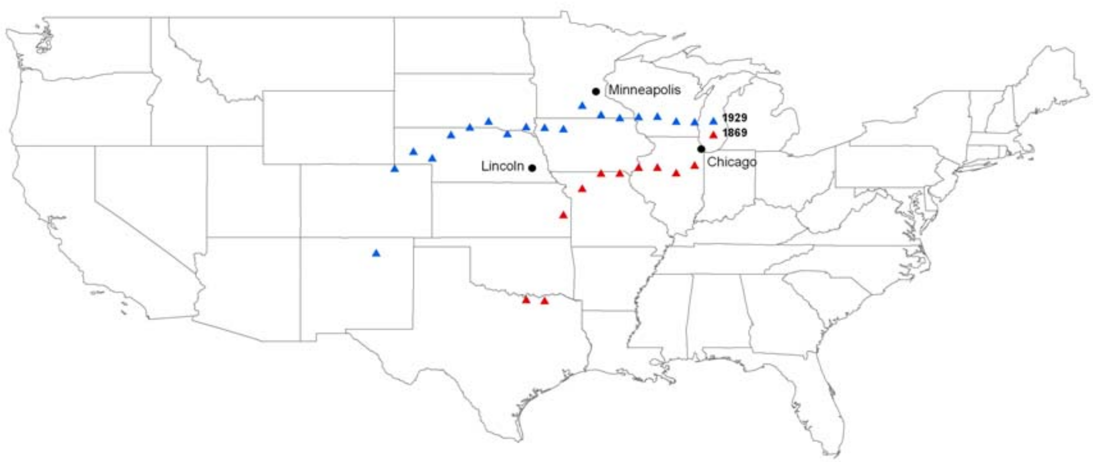
[32] The 1869 data were provided by Craig, Haines, and Weiss, *Development, Health, Nutrition*. The 1929 data are from U.S. Census Bureau, 15th Census 1930, *Agriculture*.

[33] To derive the estimates, we performed regressions for the winter wheat share of wheat output in each county in a given longitude grouping. For each degree of longitude, we used the latitude where the winter wheat share equaled one-half.

substitutions among crops—most importantly from wheat to corn—also made possible by improved technologies.[34]

Figure 3: Shift in the Spring-Winter Wheat Frontier 1869 and 1929



A Global Perspective

The biological transformation in the nineteenth and early-twentieth century grain-growing in Canada and the United States was part of a worldwide process. The farmers who extended the wheat frontier in Australia, Argentina, and Russia in the nineteenth century, faced similar challenges of producing in new and harsh environments. In all of these areas, immigrants had to adapt to new climatic challenges. 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

[34] For the substitution of corn for wheat see Olmstead and Rhode, *Creating Abundance*, pp. 80-86.

combined the favorable traits of varieties drawn from around the world. This was a purposeful and sophisticated process lead by scientists whom plant researchers today revere as the pioneering giants of their discipline. The challenges differed with farmers in Canada and in the northern Great Plains, requiring early and fast ripening hardy spring wheats. In Australia the innovations 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. 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. These institutional developments lay the foundation today's advanced research infrastructure.[35]

The global shift of wheat cultivation had dramatic effects on typical growing conditions, with on balance 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.[36] In 1926-30 world production 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 expanding production in

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[35] 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).

[36] 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.

temperate Europe, the changes in the conditions facing farmers near the frontier were significantly greater than the changes in the average conditions.[37] 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.

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. Throughout the period, the FRI data exclude China.

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.[38]

[37] 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 in North America there were substitutions within countries as production moved to harsher climates.
[38] Bennett and Farnsworth, "World Wheat," p. 283.

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.

Conclusion

This paper seeks to provide historical perspective concerning possible future human responses to climatic variation. During the nineteenth and twentieth centuries, North American farmers adopted new biological technologies to push wheat cultivation into environments previously thought too arid, too cold, and too variable to farm. The climatic challenges that these farmers overcame often rivaled the magnitude of the climatic changes predicted for the next hundred years in North America. For the most part the settlement process required adapting cultivation to colder and more arid regions—not to hotter climates as predicted in the future. But in Texas, Oklahoma, California, and other regions in the United States new varieties did facilitate production in hot dry areas. The main thrust of research in Australia was directed at overcoming hotter and more arid climates.

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 for wheat (and for other crops not analyzed here) clearly demonstrates that farmers with the aid of scientists were able to overcome significant obstacles. This record offers a testament to the achievements of an earlier generation of agronomists. 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.