Adapting to Climate:

The Transformation of North American Wheat Production, 1839-2009

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Abstract. The IPCC projects that temperatures in the major grain-growing areas of North America will rise by 3-4 degrees C by 2100. Such abrupt changes will create major challenges, significantly altering the area suitable for wheat. The historical record offers insight into the capability of agriculture to adapt to climatic challenges. Employing a new county-level data set on wheat production and climate norms, we show that during the 19th and 20th centuries North American grain farmers pushed wheat production into environments once considered too arid, too variable, and too harsh to cultivate. As summary measures, the median annual precipitation norm of the 2007 distribution of North American wheat production was one-half that of the 1839 distribution, and the median annual temperature norm was 3.7 degrees C lower. This shift, which mostly occurred before 1929, required new biological technologies. The Green Revolution associated with the pioneering work of Norman Borlaug represented an important advance in this longer process of biological innovation. But well before the Green Revolution, generations of North American farmers overcame significant climatic challenges.

The Intergovernmental Panel on Climate Change (IPCC) projects that by 2100 annual mean temperatures in North America will increase by 2-3 degrees C at mid-latitude coastal regions and by "up to more than" 5 degrees C at more northern latitudes. In the main grain-growing areas, IPCC forecasts temperatures will rise 3-4 degrees (1). A more recent MIT study suggests far greater changes will occur (2). There are a wide range of estimates of how climate changes will impact agricultural production (3-7). Numerous researchers have speculated about how farmers might change cultivars, cropping patterns, and farming methods to mitigate some of the costs of abrupt climatic changes (8). Researchers at the International Maize and Wheat Improvement Center (CIMMYT) anticipate that North American wheat farmers may extend the margin of wheat production roughly 1000 km north into northern Canada and Alaska, while heat and drought will make cultivation untenable in many areas of the southern Great Plains (9). To provide perspective to these and other predictions, this paper asks how farmers responded to past climatic challenges.

The spread of wheat cultivation across North America required that farmers repeatedly adapt to unfamiliar and hostile climatic conditions. The variations in climatic conditions that settlers encountered rivaled the magnitude of the predicted changes at given locations over the next century. We quantify the extent of the geographic variations and decipher how wheat growers learned to produce in new environments. Due to the paucity of Mexican data before 1929, most of our analysis of "North America" refers to Canada and the U.S. Inclusion of Mexico in the later part of the 20^{th} century highlights the role of the Green Revolution in pushing production into hotter and drier zones.

Results

The quantification of the geo-climatic conditions of wheat production between 1839 and 2007 shows that farmers made striking changes to adjust to climate; most of the changes in location and the technological adjustments that made settlement possible occurred before the Green Revolution.

Quantifying Geographic Changes in Production and Climate

Between 1839 and 2009, wheat output increased 26 times in the United States and over 270 times in Canada. In 1839, the geographic center (mean) of North American wheat production was located in eastern Ohio. Cultivation was concentrated in Ohio and New York; relatively little was grown as far west as Illinois. Today (2007) the center of production has moved 1800 km, into west central South Dakota (Methods). Almost all of this movement occurred when plant sciences were in their infancy.

The change in the location entailed large shifts in growing conditions. The six panels of Fig. 1 display the main features of the changing geographic distribution of the North American wheat crop across latitude; longitude; annual, January, and July temperature norms; and annual precipitation norms. The series cover the period from 1839 to 2007, utilizing county-level information from U.S. and Canada. The distributions summarized in Fig. 1 weight the fixed county-level geo-climatic characteristics by output in each locality at each date (Methods).

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

Panels C-F quantify the changes in climatic conditions associated with these geographic shifts in production. In 1839 median production took place in an environment with a (1941-70) norm of nearly 100 cm of precipitation (Panel C). In 2007, median production took place on land with a norm of less than 50 cm of precipitation; this was a drier environment than virtually any place growing wheat in the U.S. or Canada in 1839. Almost all of the changes in the distribution of production, as measured by annual precipitation, had occurred by 1929. In that year the marginal fringe (the 10 percent line) with 35 cm or less of precipitation produced about one-fifth more wheat than North America's total output in 1839. The range of annual moisture conditions widened substantially, as indicated by the growing spread between the 10 and 90 percent lines. Data on precipitation in January and July (SI 1 and SI 2) show that the decline was apparent across the year, creating an array of challenges in new production zones. As an indicator of the extent of the changes, the driest 10 percent of North American production moved from areas with 7.8 cm of rain in July in 1839 to areas that averaged 0.9 cm in 1889.

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

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

Discussion

The richly deserved testimonials for pioneering Green Revolution breeder and Nobel laureate, Norman Borlaug (1914-2009), remind us of the revolutionary accomplishments that he and other agronomists made during the past 70 years. But in 1944, when Borlaug started his work for the Rockefeller Foundation in Mexico, there was already a long history of agriculturalists successfully improving wheat to meet climatic conditions.

Biological Innovation to Adapt to Environmental Challenges

Wheat cultivation was introduced into Mexico in 1521, but it did not appear in the territory that would become Canada and the United States until 1602 (10). Discovering wheats suitable for new areas was a reoccurring struggle. Farmers in eastern Canada and New England continuously experimented to find cold-tolerant and pest-resistant wheats (11). In the more temperate Middle colonies, the cultivars (cultivated varieties) transplanted from Western Europe fared better. However, the challenges were particularly acute when pioneers moved wheat cultivation westward onto the northern Prairies, Great Plains, and Pacific Coast. All of these regions would eventually become major wheat suppliers, but only after farmers learned to overcome climatic conditions far different from those prevailing to the East and in Western Europe. The initial attempts to grow traditional wheat cultivars frequently failed.

The experiences of the Selkirk colonists who settled near Lake Winnipeg offer an example. The winter wheat, first tried in 1811-12, failed. Successive crops of spring wheat also succumbed to drought, freezing, and insects. To obtain sufficient seed for the 1820 crop, a band of Selkirk settlers had to trek over 2000 km (round trip) to Prairie du

Chien on the upper Mississippi River during the dead of winter. After about a decade of hungry times, the colony began to sustain itself (12). The prolonged troubles of the Selkirk colonists represented a clear case of settlers leapfrogging beyond the limits of their climatic knowledge. But even when settlers inched west in a more orderly fashion the challenge of adapting was daunting. In the 1840s, attempts to grow soft winter wheat on the Wisconsin Prairie repeatedly failed, and wheat culture only succeeded after farmers switched to a new hard spring wheat cultivar (13).

The Great Plains were depicted as the "Great American Desert" and considered incapable of supporting agriculture. The first waves of settlers from the humid East and Midwest moved into the High Plains during the relatively wet years of the 1880s. These farmers, along with railroad and government officials, significantly miscalculated the climatic obstacles that had to be overcome (14). Success required decades of experimentation and frequently depended on knowledge and cultivars introduced by immigrants from frigid and arid locales of Eurasia.

The spread of wheat cultivation across the Great Plains and Canadian Prairies was made possible by mechanization and the extension of railroads. A host of mechanical innovations cut in half the labor required to produce a unit of wheat between 1840 and 1913. In the 1860s railroad builders began expanding into this region; by 1913, about 133,000 km of track in the Plains and Prairies served to link farmers to expanding distant markets (15-16). But the expansion of wheat cultivation also depended on the introduction and breeding of hard red winter and spring wheats that were entirely new to North America. Over the late-19th century, the premier hard spring wheat cultivated in North America was *Red Fife* (which probably made its way from Eastern Europe to

Ontario via Scotland). According to the standard 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. It was not introduced into the U.S. until the mid-1850s. *Red Fife* was the first hard spring wheat grown in North America and became the basis for the spread of wheat into Wisconsin, Minnesota, the Dakotas, and Canadian Prairies (13).

The introduction of *Turkey* wheat was another notable breakthrough, which like *Red Fife*, allowed production to shift into more marginal environments (SI A). This hard red winter cultivar was especially well suited to the harsh growing conditions of the southern wheat belt. The standard histories credit German Mennonites, who migrated from southern Russia to Kansas, with importing *Turkey* in 1873. This transfer was far from haphazard, because local railroads recruited these migrants for their knowledge of farming in such environments (16). Furthermore, before departing the Mennonites tediously selected high-quality seed considered suitable for the new lands. Earlier Kansas settlers experimented with soft winter cultivars common to the eastern states, but these wheats proved unreliable in the cold winters and hot, dry summers. Tests at the Kansas Agricultural Experiment Station (AES) demonstrated Turkey's superiority and helped popularize the wheat. In 1919, *Turkey*-type wheat made up over 80 percent of the wheat acreage in Nebraska and Kansas, and nearly 70 percent in Colorado and Oklahoma (17-19). At this time, S. C. Salmon, a leading USDA breeder, concluded that without *Turkey* cultivars, "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 (20)."

In both Canada and the U.S. many varietal innovations were the result of government investments. In 1886 Parliament created the Canadian federal experiment station system. Its most acclaimed breeder, William Saunders, commenced a systematic program of hybridizing high-quality cultivars with early-maturing wheats introduced from around the world. In 1903 his son, Charles Saunders, took over the work at the Dominion Experimental Farm, near Ottawa. The most valuable result of their combined research efforts was *Marquis,* a cross between *Red Fife* and *Red Calcutta*, a very early wheat from India. Released in 1909, *Marquis* was an immediate success and accounted for about 90 percent of Canada's wheat acreage in 1920 (21). After testing the wheat in its network of experiment stations, the USDA released the spring wheat in 1912-13. By 1919, this cultivar accounted for 17 percent of U.S. acreage, and its range stretched from Washington State to northern Illinois (19). The rapid spread of *Marquis* was not an isolated case. Around 1900, Mark Alfred Carleton, the USDA's most prominent wheat breeder and plant explorer, introduced scores of cultivars from the Russian Empire. He was explicitly seeking cultivars that thrived in harsh environments. After proving drought and rust resistant in controlled tests, several durum introductions rapidly diffused in Minnesota and the Dakotas (13, 22).

Table 1, which lists a number of important new wheat cultivars, hints at the growing importance of public breeding (18, 23-24). (The distinction between the public and private sectors is not precise because breeders in both sectors employ germplasm from the other.) In 1919, 27 percent of U.S. wheat acreage was planted to cultivars introduced or bred by the public sector and almost all of Canadian wheat was a product of government breeders (19, 21). Public breeding activities in the U.S. increased over much of the 20th century. In 2008 varietal surveys of U.S. and Canadian wheat (SI B) indicate that roughly 84 percent of wheat acreage is planted to cultivars bred by the public sector. Improvements in breeding technologies along with environmental and economic factors have accelerated the rate of turnover of wheat cultivars. The surveys show that the median vintage of modern wheats is 12 years. By comparison, the 1919 median vintage was about three decades. Changes in technologies have allowed farmers to adopt seeds tailored to narrower geo-climatic niches; none of the over 300 cultivars reported in the 2008 surveys accounted for more than 6 percent of total U.S. and Canadian wheat acreage. Breeding advances in the U.S. and Mexico accelerated the evolution of wheat germplasm and the plant's adaptability to more varied conditions.

The Home of the Green Revolution

Although wheat appeared early in Mexico, the crop was always secondary to maize. By the early 1940s, rust diseases were taking a heavy toll and national production accounted for less than one-half of consumption. In 1943, the Mexican government together with the Rockefeller Foundation established a wheat breeding program, hiring Norman Borlaug as the chief breeder the following year. His invention of shuttle breeding (whereby researchers took seed grown at high elevations over the summer to grow at low elevations over the winter and then planted the resulting seed at high elevations the following spring, and so on) allowed Borlaug to cut the breeding time in half and develop plants adapted to a wider range of environmental conditions. Borlaug bred a series of early-ripening, fertility-responsive, rust-resistant cultivars, but these were prone to lodging (the bending and breaking of the stems). Building on the work of Orville Vogel at the Washington State AES, Borlaug began to produce semi-dwarf lines in 1954 based on a cross of *Norin 10* (from Japan) and *Brevor* (from the Washington State AES). The resulting plants had strong straw, high yield potential, and good rust resistance, including protection against the new stem rust race, 15b, which was ravaging North America. A succession of new lines began to diffuse rapidly, increasing production, and transforming Mexico into a net exporter by the early 1960s. With the transfer of the Mexican seeds and breeding approaches to India and Pakistan, the Green Revolution was born (25-27).

Table 2, which incorporates data on Mexican production, highlights the role of the Green Revolution in pushing production into hotter and drier zones. In 1929, Mexico accounted for only one percent of the sum of U.S., Canadian, and Mexican output, so Mexico's inclusion has little effect on the overall North American distributions. But its share grew about four-fold by 1969 and even more by 2007, so its inclusion in the latter years is important, particularly for the distributions of latitude, temperature, and precipitation. The row marking the southern 10 percent of production shows latitude of the distribution including Mexico in 2007 was 1.37 degrees south (about 150 km) of that excluding Mexico. The row on 90 percent by annual temperature quantifies the movement into hotter domains. The temperature line for the hottest 10 percent of North American production including Mexico increased by 2.39 degrees C between 1929 and 2007—this was 1.39 degrees more than with Mexico excluded. Finally, the row for the lowest 10 percent of wheat production measured by annual precipitation shows a greater expansion into drier areas. Including Mexico substantially widens the conditions under which North American wheat was grown after 1929, essentially continuing trends that had been underway over the previous century.

Adaptation

Adjusting to climate change will require shifts in the location of production along with changes in germplasm, sowing dates, tillage practices, and water management at specific locations (28-29). We can obtain a sense of the significance of past adjustments by examining the shifts from spring to winter wheat cultivars. When the upper Midwest, the northern Great Plains, and the Canadian Prairies were first settled, hard red spring wheat was generally the only reliable option. Wherever feasible, farmers prefer to grow winter wheat instead of spring wheat. Winter wheat generally offers significantly higher yields and is less subject to damage from insects and diseases, but in colder climates it suffers high losses to winterkill.

Agronomists have long recognized that the development of hearty winter cultivars that could be grown in harsher climates was an historic achievement. Our detailed data on production and cultivars allow us to quantify the extent of the change. Fig. 2 maps the North American spring-winter wheat frontiers for 1869 and 1929 (Regression Analysis). Spring wheat output generally exceeded winter wheat output in the counties north of the estimated frontier, and winter wheat dominated south of the frontier. Between 1869 and 1929 scientific advances allowed winter wheat production to spread 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 over one-fifth of all North American wheat output in 1929. Since 1929, winter wheat has been adapted for large areas in South Dakota and Montana (30).

This displacement of one wheat type by another represented one of many ways that farmers employed technology to adapt to climatic conditions.   Within each class of wheat, farmers have generally adopted later planting dates over the 20th century (31-32). Mechanical technologies allow more rapid and timely performance of tillage operations. Low tillage practices and irrigation have become increasingly common. In addition, farmers in many areas have increased efficiency by substituting out of wheat into other activities.

Due to climate change some areas presumably will decrease or cease wheat production, while other areas, particularly in northern Canada and Alaska, are expected to enter production. Although the anticipated movement in the wheat frontier is substantial, it is unlikely to be as great as the past geographic shifts in production. The difficulties in extending the transportation infrastructure to facilitate future shifts also appear less imposing than those overcome to open the Plains and Prairies. The challenging problems deal with adapting growing practices and creating improved cultivars.

Table 3, which relates the predicted changes in annual mean climatic conditions to the current geographic variation across five sample locations, offers some guidance on agricultural adaptability.   The table reports the baseline (1981-90) annual mean temperature and precipitation (Baseline Climate Data) , and the conditions in 2091-2100 as estimated in the high-resolution atmospheric general circulation model (33-34) used by the World Bank among others. Columbus, OH serves as useful point of comparison because its 1981-90 conditions closely approximated the annual mean climatic conditions that existed near the geographic center of the distribution of North American wheat production in 1839 (35). The last two columns of the table, which show the differences between the Columbus baseline and the other four locations, illustrate the wide array of climatic conditions to which wheat has been adapted in North America over the past 170 years. Even with the predicted annual mean temperature by 2100, farmers near Edmonton, AB and Dickerson, ND will confront substantially colder conditions than eastern wheat growers faced circa 1839. Even with the anticipated increase in precipitation, the northern farmers will have to make do with about half the precipitation that the earlier generation of eastern farmers received. The predicted changes in Dodge City, KS and Ciudad Obregón, Sonora suggest both hotter and drier conditions than were common at the center of North American production in 1839 (again, a climate akin to that in Columbus in the baseline period). But note that the difference in temperature between Columbus and Ciudad Obregón was roughly six times the increase predicted in the latter city by 2100. Wheat production is sensitive to seasonal fluctuations in weather conditions, which will likely become more variable in the future, and which are not captured by annual mean data (29). Nevertheless, the historical record of adapting wheat cultivation to areas with widely varying climates is impressive.

Conclusions

During the 19th and 20th centuries, new technologies allowed North American farmers to repeatedly push wheat cultivation into environments once thought too arid, too variable, and too harsh to farm. Most notably, the median precipitation norm of the 1929 distribution of North American wheat production was one-half that of the 1839 distribution —that is about 50 fewer cm. 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. Farming with less water is more of a problem if the temperature is also hotter. However, biological innovations were also crucial to the expansion of production in hot-arid areas such as Texas, Oklahoma, central California, and northern Mexico. The currently predicted changes over the next century will in a sense reverse the predominant historical path of the past two centuries by creating a warmer and wetter environment in the Plains and Prairies that will partially approach the conditions that existed in the Middle Atlantic region when it constituted the North American wheat belt.

There will be enormous challenges to the agricultural sector associated with impending climate changes. Public and private research will be crucial to addressing the new environmental realities, as it was in facilitating the past movement in production. Given the challenges ahead and the long lags between investments in research and their payoffs, reinvigorating public support for research to promote agricultural adaptability should be a high policy priority (36).

Methods

Production Data. A primary task was to construct a consistent local-level wheat productions series for North America. We extract county-level U.S. wheat production data for 1839 to 1909 from Inter-University Consortium for Political and Social Research [ICPSR], *Historical Demographic, Economic, and Social Data, 1790-2000*, ICPSR 2896. The U.S. data for after 1909 come from the *Censuses of Agriculture*, various years. Canadian data are from *Agricultural Census of Canada*, supplemented by sundry provincial sources to fill gaps in the Census data between 1950 and 1976. To link the output data for the period before 1978, we combine the Canadian 1850 production with the U.S. production for 1849 and so on. The number of local entities varies over time, but taking 1929 as an example, we record data on 3,070 counties in the U.S. and 216 units in Canada. We have wheat production data for every ten years from 1839 to 1978 and for every five years thereafter. We base our 1839 Canadian output estimate on data for Upper Canada (Ontario) in 1842 and Lower Canada (Quebec) in 1844.

For the U.S., we linked production to each county's location based of its 1970 population centroid as reported in U.S. Department of Health and Human Services, *Bureau of Health Professions Resource File*, ICPSR 9075. For Canada the data are less standardized and the local units reported by official sources include counties, census divisions, and agricultural districts depending on the province and year. We linked production to a fixed location with each local unit.

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

Mexican Data. We do not include Mexico in our primary long-run analysis due to a paucity of data until 1929, and Mexico's relatively low wheat output for most of the period. Production data for 1929 are from Banco Nacional de Credito Agricola, S.A. *El*

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Baseline Climate Data. The baseline (1981-90) annual temperatures and precipitation for Columbus OH; Dickerson, ND, Edmonton, AB, Fort Dodge, KS; and Ciudad Obregón are from World Weather Records, http://dss.ucar.edu/datasets/ds570.1/

Regression Analysis. Fig. 2 connects the latitude at which spring wheat output equaled winter wheat output for each longitude between 87 to 105 degrees. The points are derived from regressions of the proportion of spring wheat in total county wheat production in the 1869 and 1929 for U.S. and Canada observations binned by degree of longitude.

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Table 1. Important new wheat cultivars

Introduction in North America	Name	Origin	Class	Public or Private	Introduced or Bred
1819	*Mediterranean*	Italy	Soft Red Winter	Private	Introduced
1842	*Red Fife*	Ukraine	Hard Red Spring	Private	Introduced
1871	*Fultz*	USA	Soft Red Winter	Private	Bred
1873	*Turkey*	Russia	Hard Red Winter	Private	Introduced
1898	*Kubanka*	Russia	Durum	Public	Introduced
1900	*Kharkof*	Russia	Hard Red Winter	Public	Introduced
1909	*Marquis*	Canada	Hard Red Spring	Public	Bred
1914	*Federaton*	Australia	Soft White	Public	Bred
1917	*Blackhull*	USA	Hard Red Winter	Public	Bred
1932	*Tenmark*	USA	Hard Red Winter	Public	Bred
1934	*Thatcher*	USA	Hard Red Spring	Public	Bred
1940	*Triumph*	USA	Hard Red Winter	Public	Bred
1942	*Pawnee*	USA	Hard Red Winter	Public	Bred
1953	*Selkirk*	Canada	Hard Red Spring	Public	Bred
1961	*Gaines*	USA	Soft White Winter	Public	Bred
1964	*Sonora 64*	Mexico	Hard Red Spring	Public	Bred
1964	*Scout /Scout 66*	USA	Hard Red Winter	Public	Bred
1969	*Neepaw*	Canada	Hard Red Spring	Public	Bred
1970	*Era*	USA	Hard Red Spring	Public	Bred
1977	*Newton*	USA	Hard Red Winter	Public	Bred
1984	*TAM 107*	USA	Hard Red Winter	Public	Bred
1994	*Jagger*	USA	Hard Red Winter	Public	Bred
1994	*AC Barrie*	Canada	Hard Red Spring	Public	Bred
2003	*Lilian*	Canada	Hard Red Spring	Public	Bred
2003	*Jagalene*	USA	Hard Red Winter	Private	Bred
2004	*Strongfield*	Canada	Durum	Public	Bred

Sources: (18-19, 23, 24, SI B)

Table 2. Incorporating Mexican wheat production, 1929-2007

			North America (incl. Mexico)			Canada and U.S. only		
			1929	1969	2007	1929	1969	2007
Latitude	South	10%	36.76	35.56	34.64	37.06	36.39	36.01
Degrees	Median	50%	44.96	43.03	45.07	45.14	43.98	45.63
	North	90%	52.30	50.01	51.65	52.38	50.23	51.65
Longitude	East	10%	85.87	88.94	89.04	85.81	88.48	88.70
Degrees	Median	50%	101.32	101.18	101.54	101.34	100.93	101.35
	West	90%	114.17	113.30	114.92	114.17	113.30	114.92
Annual	Coldest	10%	1.56	2.56	1.78	1.56	2.22	1.78
Temperature	Median	50%	8.61	9.39	7.94	8.50	9.06	7.56
Degrees C	Hottest	90%	14.00	15.72	16.39	13.94	15.22	14.94
Annual	Driest	10%	35.2	33.6	31.1	35.3	34.8	32.3
Precipitation	Median	50%	48.8	47.3	46.0	48.8	47.8	46.3
Cm	Wettest	90%	93.7	93.7	94.6	93.8	94.0	95.6

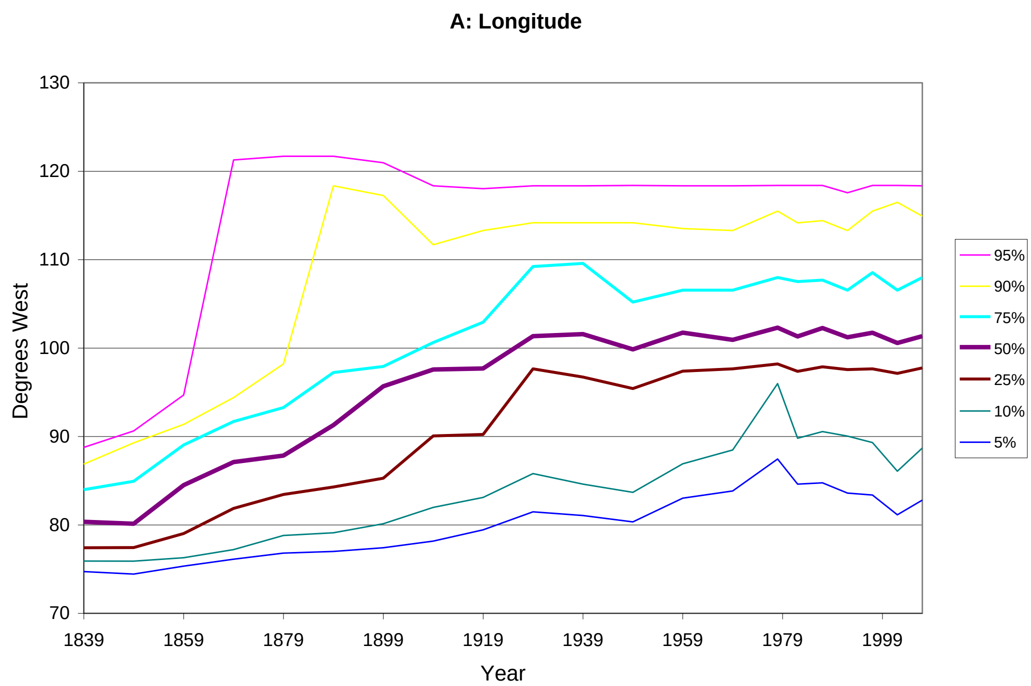
Source: Methods

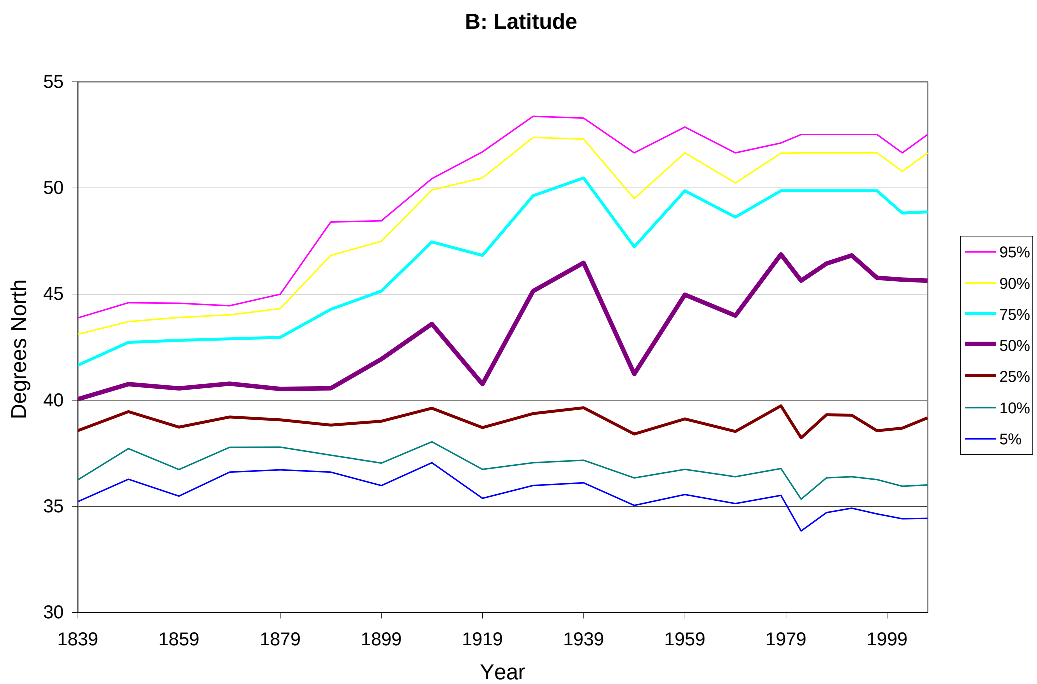
Table 3. Climatic changes and geographic variation

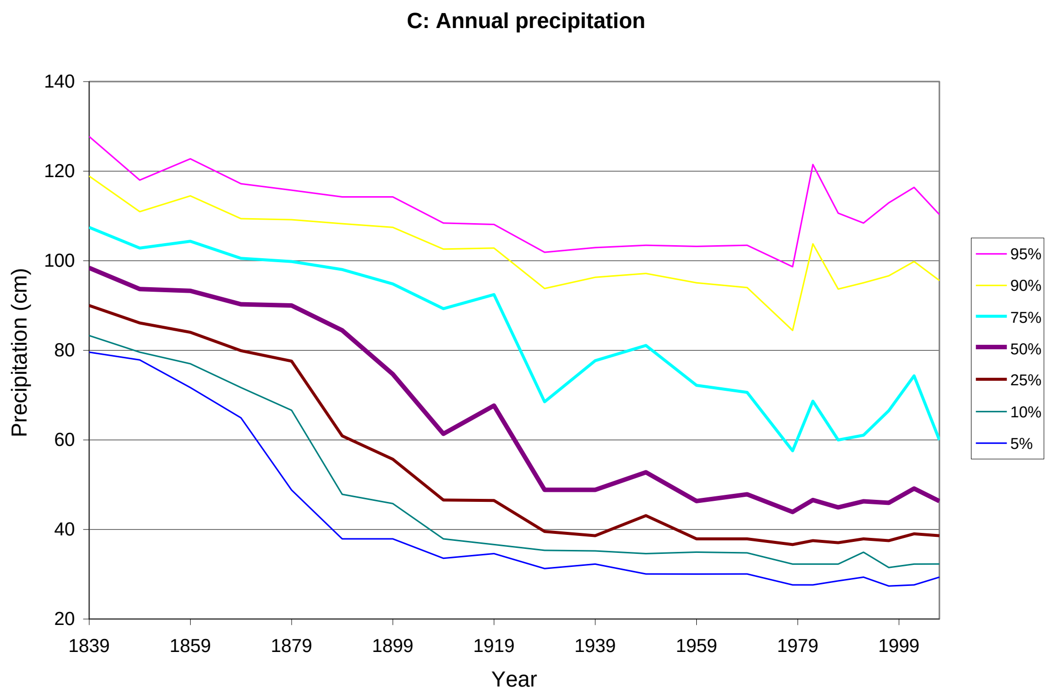
	Mean Annual Conditions 1981-90 Baseline		Predicted Changes 1981-91 to 2090-2100		Differences from Columbus in 1981-90	
	Deg C	Prec (cm)	Deg C	Prec (%)	Deg C	Prec (%)
Columbus, Ohio	11.2	97.2	3	12	0	0
Edmonton, Alberta	4.4	46.7	3	13	-6.8	-52
Dickerson, North Dakota	5.2	40.6	3	11	-6.0	-58
Dodge City, Kansas	13.0	53.6	3	4	1.8	-45
Ciudad Obregon, Sonora	23.6	33.7	2	33	12.4	-65

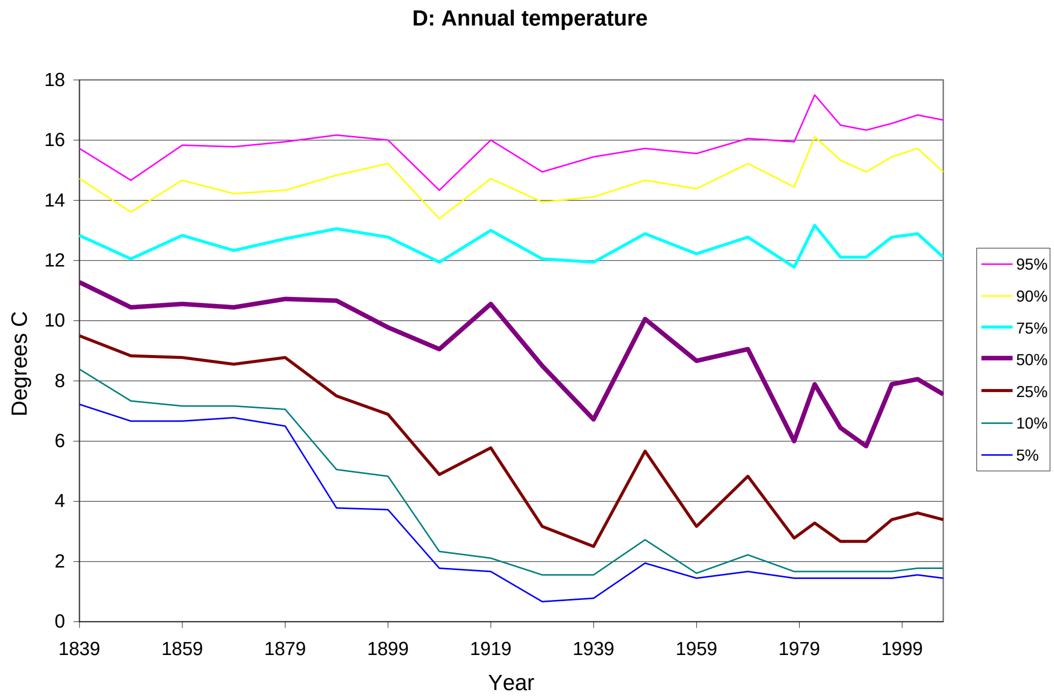
Sources: Baseline Climate Data and (33, 34)

Fig. 1. Changing distribution of North American wheat production, 1839-2007

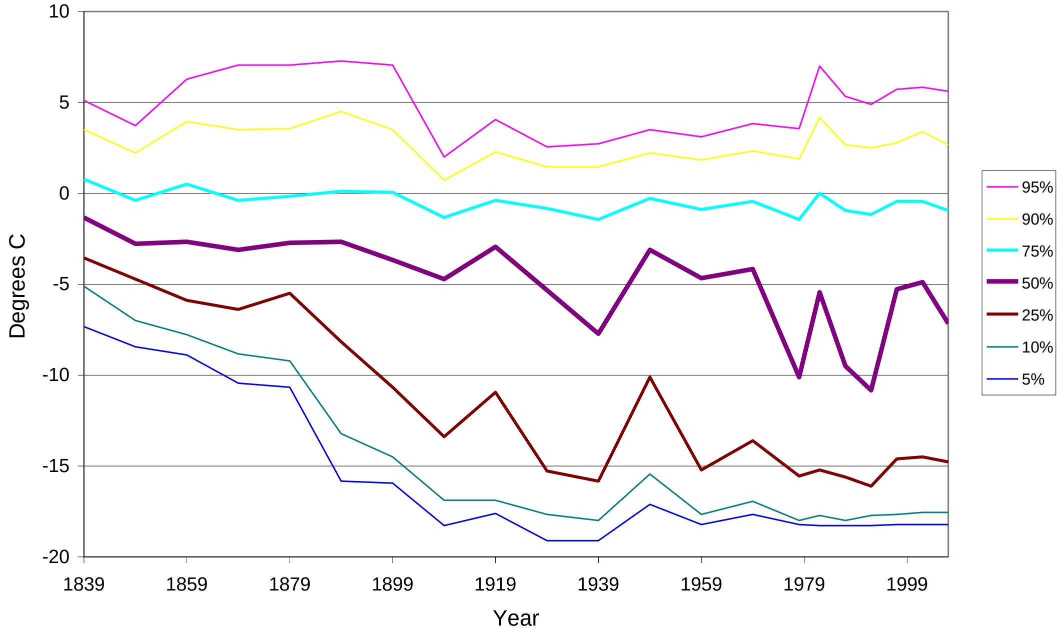





C: Annual precipitation
Precipitation (cm)
140
120
100
80
60
40
20
1839
1859
1879
1899
1919
1939
1959
1979
1999
Year
95%
90%
75%
50%
25%
10%
5%


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

E: January temperature



F: July temperature

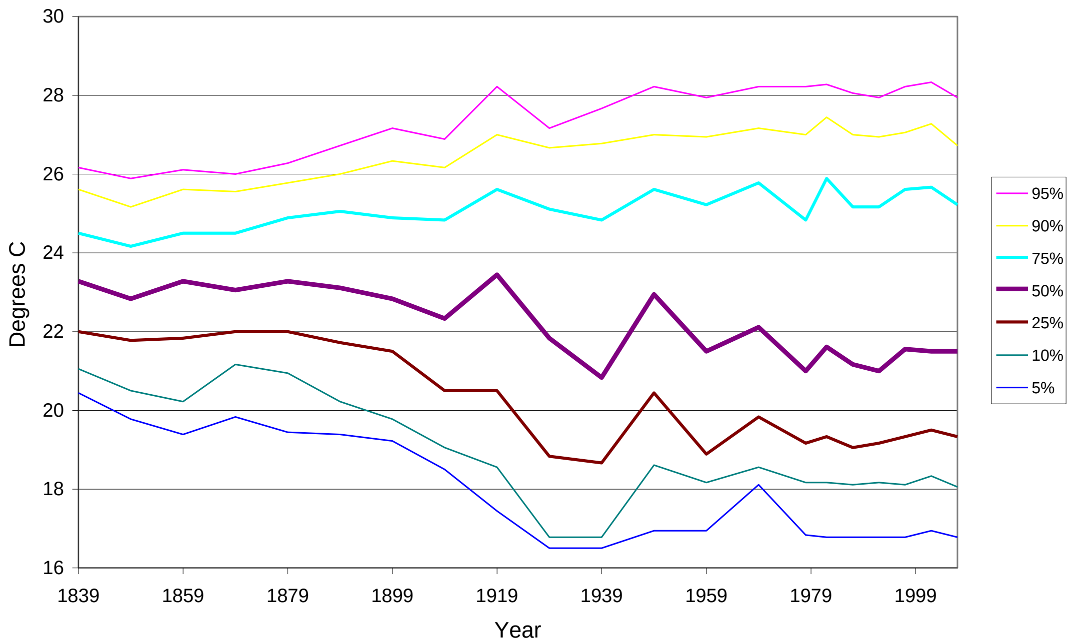


Fig. 2. Shift in the North American spring-winter wheat frontier, 1869-1929

Supporting Text

SI A. Counterfactual Wheat Yield Analysis

Using U.S. data on county-level wheat output and acreage harvested (which first become available in 1879), we can gauge the effect of the change in the location of production on yields over the late 19^{th} and early 20^{th} centuries. We estimate, for each U.S county i, the mean yields per acre, y_i, over six census years 1879, 1889, 1899, 1909, 1919, and 1929. We then calculate county's share, θ_{it}, of national acreage for years t=1879 and 1929. The index, $Y_t=\sum_i \theta_{it} \mathbf{y}_i$, measures national yields under the counterfactural that the acreage distribution in year t is weighted by mean yields. The ratio $Y_{1929}/Y_{1879}=0.857$, indicating that the distibution of wheat acreage in 1929 was associated with a 14 percent lower mean yield than the distribution of 1879.

The clear implication is that U.S. production was shifting to more marginal lands between 1879 and 1829. This counterfactual exercise does not control for the negative impacts of a worsening pest environment and nitrogen depletion, or for the positive effects of improved cultivars. The net effect of these and other changes essentially offset the movement to more marginal lands, resulting in a trivial decline (0.4 percent) in actual yields between 1879 and 1929.

SI B.
2008 Wheat Cultivar Surveys

We assembled 2008 data on wheat acreage planted by varieties from the surveys in the following U.S. States and Canadian Provinces (which collectively accounted for over 77 percent of total acreage):

California
www.californiawheat.org/Variety Surveys/VarSurvey2008.pdf

Colorado
www.nass.usda.gov/Statistics_by_State/Colorado/Publications/Annual_Statistical_Bulletin/
2008bulletin.pdf

Idaho
www.nass.usda.gov/Statistics_by_State/Idaho/Publications/Wheat_and_Barley_Variety/
pdf/2008%20Wheat%20supplement.pdf

Kansas
www.nass.usda.gov/Statistics_by_State/Kansas/Publications/Crops/Whtvar/whtvar08.pdf

Minnesota
www.smallgrains.org/files/docs/2008wheatsurvey.pdf

Montana
http://wbc.agr.mt.gov/Producers/Variety_releases/2008%20Wheat%20Varieties.pdf

Nebraska
www.nass.usda.gov/Statistics_by_State/Nebraska/Publications/Crop_Variety_Reports/whet2008.pdf

North Dakota
www.nass.usda.gov/Statistics_by_State/North_Dakota/Publications/Crop_Varieties/rel/whtvar08.pdf

Oklahoma
www.nass.usda.gov/Statistics_by_State/Oklahoma/Publications/Oklahoma_Wheat_Varieties/
2009/ok_wheat_varieties_09.pdf

Oregon
www.nass.usda.gov/Statistics_by_State/Oregon/Publications/Field_Crop_Report/
wheat%20and%20barley%20variety/07_11wv.pdf

South Dakota
http://www.nass.usda.gov/Statistics_by_State/South_Dakota/Publications/Crop_Variety_Reports/
Pub/whtvar08.pdf

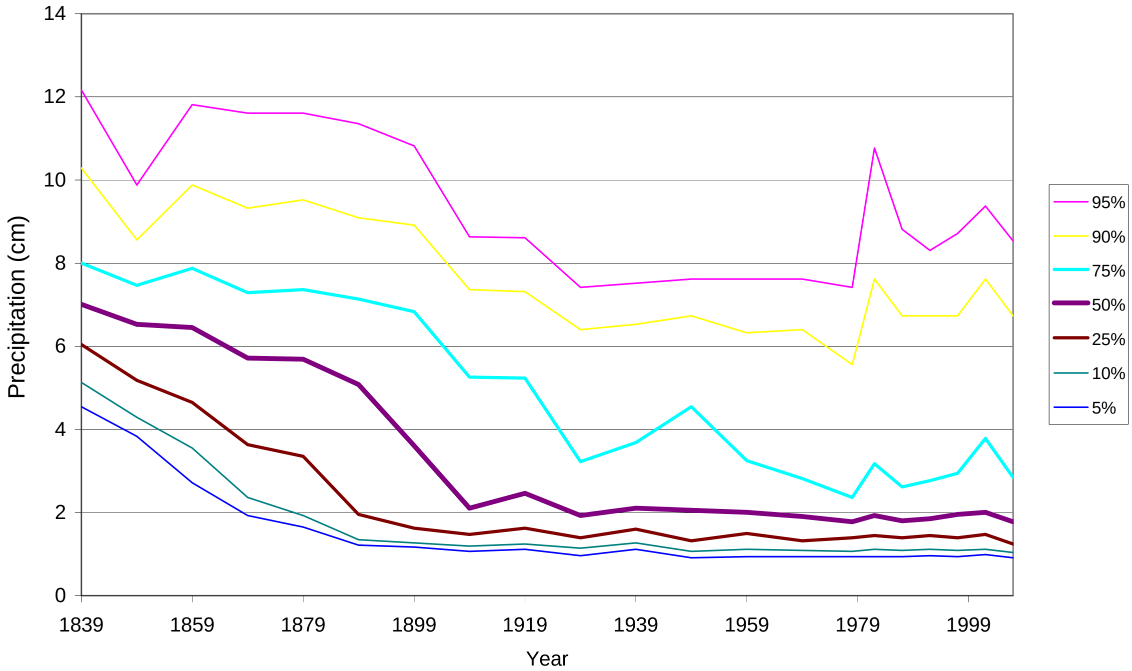
Washington
www.nass.usda.gov/Statistics_by_State/Washington/Publications/Small_Grains/whtvar08.pdf

Wyoming
www.nass.usda.gov/Statistics_by_State/Wyoming/Publications/Crops/Winter_wheat_var/wht-var08.pdf

Canada Prairie Provinces (including Saskatchewan, Manitoba, Alberta) and British Columbia
www.cwb.ca/public/en/farmers/surveys/variety/archive/pdf/2008/results.pdf
linked to data on acreage seeded to wheats by category from Statistics Canada,
CANSIM Table 001-0010

We added information on date of release and public/private origin from the USDA, Agricultural Research Service, Germplam Resource Information Network http://www.ars-grin.gov/;Canadian Food Inspection Agency, http://www.inspection.gc.ca/english/plaveg/pbrpov/cropreport/whe/; and SECAN http://www.secan.com/data/varieties/

SI 1: January precipitation



SI 2: July precipitation