Adapting North American wheat production to climatic challenges, 1839–2009

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The Intergovernmental Panel on Climate Change projects that temperatures in the major grain-growing areas of North America will rise by 3–4 °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. Using a new county-level dataset 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 °C lower. This shift, which occurred mostly 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. However, well before the Green Revolution, generations of North American farmers overcame significant climatic challenges.

adaptation | agricultural technology | food security

The Intergovernmental Panel on Climate Change (IPCC) projects that by 2100 annual mean temperatures in North America will increase by 2 to 3 °C at midlatitude coastal regions and by "up to more than" 5 °C at more northern latitudes. In the main grain-growing areas, the IPCC forecasts temperatures will rise 3 to 4 °C (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 1,000 km north into northern Canada and Alaska, whereas heat and drought will make cultivation untenable in many areas of the southern Great Plains (9). To provide perspective on 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. Because of the paucity of Mexican data before 1929, most of our analysis of "North America" refers to Canada and the United States. Inclusion of Mexico in the later part of the 20th century highlights the role of the Green Revolution in pushing production into hotter and drier zones.

Results

The quantification of the geoclimatic 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-fold in the United States and more than 270-fold 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 wheat was grown as far west as Illinois. In 2007 the center of production had moved 1,800 km west, into west-central South Dakota (*Methods*). Almost all 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 1839–2007, using county-level information from United States and Canada. The distributions summarized in Fig. 1 weight the fixed county-level geoclimatic characteristics by output in each locality at each date (*Methods*).

Fig. 1*A* summarizes the changing longitude of wheat production in North America over roughly 170 y. The median production shifted west by 21° of longitude (nearly 1,800 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 (Fig. 1*B*) was relatively constant until the 1890s, when the northern Plains and the Canadian Prairies began to enter cultivation. The median latitude of production in 1929 was near the northern fringe of production (the 95% line) in 1839. The northernmost one-quarter of production (reflected by the 75% line) moved north by 8° of latitude (>880 km) between 1839 and 1929.

Fig. 1 *C–F* quantifies the changes in climatic conditions associated with these geographic shifts in production. In 1839 median production took place in an environment with a (1941–1970) norm of nearly 100 cm of precipitation (Fig. 1*C*). In 2007, median production took place on land with a norm of less than 50 cm of precipitation; this environment was drier than virtually any place growing wheat in the United States or Canada in 1839. Almost all the changes in the distribution of production, as measured by annual precipitation, had occurred by 1929. In that year the marginal fringe (the 10% 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% lines. Data on precipitation in January and July (Figs. S1 and S2) 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% 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 °C and 5.9 °C, respectively, between 1839 and 2007 (Fig. 1 *D* and *E*). The range of temperature conditions widened greatly, with a pronounced movement into colder domains. The 90–10 percentile differential in annual temperature doubled, from 6.3 to 13.1 °C,

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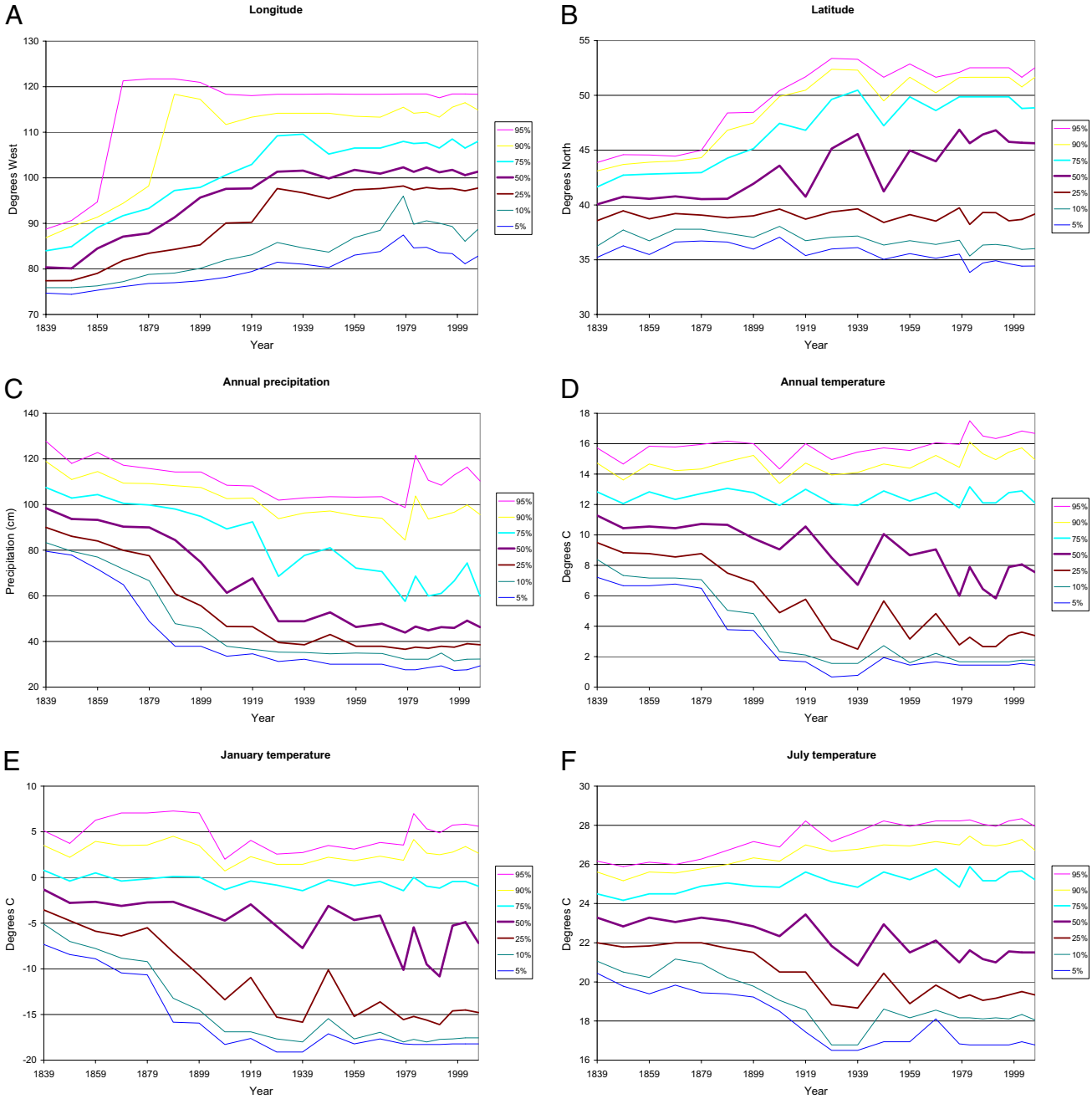

Fig. 1. Changing distribution of North American wheat production, 1839–2007.

during the past 170 y. Again, most of the change occurred before the dawn of modern plant sciences. Focusing on annual temperature norms, the coldest 10% of production occurred at 8.4 °C in 1839 but at 1.6 °C in 1929. The fall in winter temperature was more extreme (Fig. 1*E*). For the coldest 10% of production as measured by January temperature, the norm in 1839 was −5.1 °C but in 1929 was −17.7 °C, a fall of 12.6 °C. In 1929 much more wheat was grown in places where the January temperature norm averaged less than −17 °C than was grown in all of North America in 1839, a date when little wheat was produced in areas with a January temperature norm as low as −7 °C. The colder production locations also have 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 a positive association between temperature and precipitation remained.

The changes have not been limited to production 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. Fig. 1*F* shows that, although the median July temperature norm in the wheat-growing area 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 °C or hotter. By 1929 more than 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 y. However, in 1944, when Borlaug started his work for the Rockefeller Foundation in Mexico, there already was a long history of agriculturalists who had successfully improved 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 these regions eventually became 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 1811–1812, 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 more than 2,000 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. However, 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 failed repeatedly, and wheat culture succeeded only after farmers switched to a new hard spring wheat cultivar (13).

The Great Plains were depicted as the "Great American Desert" and were 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). However, 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. During 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, ON, selected and increased the grain stock from a single wheat plant grown on their farm in 1842. 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 wheat into Wisconsin, Minnesota, the Dakotas, and Canadian Prairies (13).

Another notable breakthrough was the introduction of *Turkey* wheat, which, like *Red Fife*, allowed production to shift into more marginal environments (*SI Text*). 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 (ref. 16, pp. 88–89.). Furthermore, before departing for Kansas, 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 more than 80% of the wheat acreage in Nebraska and Kansas and nearly 70% of the wheat acreage in Colorado and Oklahoma (17, 18 and ref. 19, pp. 208–218). At this time, S. C. Salmon, a leading US Department of Agriculture (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 United States 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% 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 1912–1913. By 1919, this cultivar accounted for 17% of United States 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 explicitly was seeking cultivars that thrived in harsh environments. After proving drought and rust resistant in controlled tests, several durum introductions diffused rapidly 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 use germplasm from the other.) In 1919, 27% of the wheat acreage in the United States was planted in cultivars introduced or bred by the public sector, and almost all Canadian wheat was a product of government breeders (ref. 19, pp. 208–218, and ref. 21, pp. 73–74). Public breeding activities in the United States increased during much of the 20th century. In 2008 varietal surveys of United States and Canadian wheat (*SI Text*) indicate that roughly 84% 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 y. By comparison, the 1919 median vintage was about 3 decades. Changes in technologies have allowed farmers to adopt seeds tailored to narrower geoclimatic niches; none of the more than 300 cultivars reported in the 2008 surveys accounted for more than 6% of total United States and Canadian wheat acreage. Breeding advances in the United States and Mexico accelerated the evolution of wheat germplasm and the plant's adaptability to more varied conditions.

Home of the Green Revolution. Although wheat appeared early in Mexico, the crop always was 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 then repeated the process) 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

Table 1. Important new wheat cultivars

Introduction in North America	Cultivar	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*	United States	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*	United States	Hard Red Winter	Public	Bred
1932	*Tenmark*	United States	Hard Red Winter	Public	Bred
1934	*Thatcher*	United States	Hard Red Spring	Public	Bred
1940	*Triumph*	United States	Hard Red Winter	Public	Bred
1942	*Pawnee*	United States	Hard Red Winter	Public	Bred
1953	*Selkirk*	Canada	Hard Red Spring	Public	Bred
1961	*Gaines*	United States	Soft White Winter	Public	Bred
1964	*Sonora 64*	Mexico	Hard Red Spring	Public	Bred
1964	*Scout /Scout 66*	United States	Hard Red Winter	Public	Bred
1969	*Neepaw*	Canada	Hard Red Spring	Public	Bred
1970	*Era*	United States	Hard Red Spring	Public	Bred
1977	*Newton*	United States	Hard Red Winter	Public	Bred
1984	*TAM 107*	United States	Hard Red Winter	Public	Bred
1994	*Jagger*	United States	Hard Red Winter	Public	Bred
1994	*AC Barrie*	Canada	Hard Red Spring	Public	Bred
2003	*Lilian*	Canada	Hard Red Spring	Public	Bred
2003	*Jagalene*	United States	Hard Red Winter	Private	Bred
2004	*Strongfield*	Canada	Durum	Public	Bred

Data from refs. 18, 19, 23, 24, and surveys listed in *SI Text*.

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 semidwarf 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 1% of the sum of United States, Canadian, and Mexican output, so Mexico's inclusion has little effect on the overall North American distributions. However, its share grew about fourfold 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 in Table 2 marking the southern 10% of production shows that the latitude of the distribution including Mexico in 2007 was 1.37° south (about 150 km) of that excluding Mexico. The row showing 90% by annual temperature quantifies the movement into hotter domains. The temperature line for the hottest 10% of North American production including Mexico increased by 2.39 °C between 1929 and 2007, 1.39 °C higher than with Mexico excluded. Finally, the row for the lowest 10% 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 generally was 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

Table 2. Data incorporating Mexican wheat production, 1929–2007

	North America (including Mexico)			Canada and United States only		
	1929	1969	2007	1929	1969	2007
Latitude (degrees)						
Southernmost 10%	36.76	35.56	34.64	37.06	36.39	36.01
Median 50%	44.96	43.03	45.07	45.14	43.98	45.63
Northernmost 90%	52.30	50.01	51.65	52.38	50.23	51.65
Longitude (degrees)						
Easternmost 10%	85.87	88.94	89.04	85.81	88.48	88.70
Median 50%	101.32	101.18	101.54	101.34	100.93	101.35
Westernmost 90%	114.17	113.30	114.92	114.17	113.30	114.92
Annual temperature (°C)						
Coldest 10%	1.56	2.56	1.78	1.56	2.22	1.78
Median 50%	8.61	9.39	7.94	8.50	9.06	7.56
Hottest 90%	14.00	15.72	16.39	13.94	15.22	14.94
Annual precipitation (cm)						
Driest 10%	35.2	33.6	31.1	35.3	34.8	32.3
Median 50%	48.8	47.3	46.0	48.8	47.8	46.3
Wettest 90%	93.7	93.7	94.6	93.8	94.0	95.6

Data from refs. 37–45.

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

(by 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 into large regions of Illinois, Wisconsin, and Colorado. The area between the 1869 and 1929 spring–winter wheat frontiers accounted for more than 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 used technology to adapt to climatic conditions. Within each class of wheat, farmers generally have adopted later planting dates during 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 other crops for wheat.

Because of climate change, some areas presumably will decrease or cease wheat production, whereas 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 (1981–1990) 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 1981–1990 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 during the past 170 y. 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, Mexico, 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, OH, in the baseline period). Note, however, 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 probably will 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 push wheat cultivation repeatedly 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/y. 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 also is hotter. However, biological innovations also were crucial to the expansion of production in hot-arid areas such as Texas, Oklahoma, central California, and northern Mexico. The currently predicted changes during 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 address 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 production series for North America. We extracted county-level United States wheat production data (37, 38) and www.agcensus.usda.gov/Publications/2007/index.asp. Canadian data are from refs. 39 and 40 supplemented by

Table 3. Climatic changes and geographic variation

	Mean annual conditions 1981–1990 baseline		Predicted changes 1981–1991 to 2090–2100		Differences from Columbus in 1981–1990	
Location	°C	Precipitation (cm)	°C	Precipitation (%)	°C	Precipitation (%)
Columbus, OH	11.2	97.2	3	12	0	0
Edmonton, Alberta	4.4	46.7	3	13	−6.8	−52
Dickerson, ND	5.2	40.6	3	11	−6.0	−58
Dodge City, KS	13.0	53.6	3	4	1.8	−45
Ciudad Obregon, Sonora, Mexico	23.6	33.7	2	33	12.4	−65

Sources: Baseline Climate Data and refs. 33 and 34.

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 United States production for 1849, and so forth. The number of local entities varies over time; in 1929, for example, we record data on 3,070 counties in the United States and 216 units in Canada. We have wheat production data for every 10 y from 1839–1978 and for every 5 y thereafter. We base our 1839 Canadian output estimate on data for Upper Canada (Ontario) in 1842 and Lower Canada (Quebec) in 1844.

For the United States, we linked production to each county's location based on its 1970 population centroid from ref. 41. 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 geoclimatic variables reflect average 1941–1970 conditions in each county or agricultural district as recorded by the US National Oceanic and Atmospheric Administration in ref. 41 or the Canadian Atmospheric Environment Service (42). 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 because of a paucity of data until 1929 and Mexico's relatively low wheat output for most of the period. Production data for 1929 are from ref. 43, those for 1969 are from ref. 44, and those for 2007 are from Sistema de Información Agroalimentaria de Consulta, www.siap.gob.mx. Weather norms are from ref. 45.

Baseline Climate Data. The baseline (1981–1990) 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° W and 105° W. The points are derived from regressions of the proportion of spring wheat in total county wheat production in the 1869 and 1929 for United States and Canada; observations are binned by degree of longitude.

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