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Chapter Authors: Alan L. Olmstead, Paul W. Rhode

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Responding to Climatic Challenges
Lessons from U.S. Agricultural Development

Alan L. Olmstead and Paul W. Rhode

Prominent climate researchers project that by the end of the twenty-first century, temperatures on the North American continent will be 4 to 6°F higher at its coasts and 9°F higher at the more northern latitudes.[1] Sea levels may rise between 0.5 and 2 feet. Such changes will have profound impacts on economic activity, including agricultural production. Researchers at the International Maize and Wheat Improvement Center anticipate North America wheat farmers will have to cease production at the southern end of the grain belt but may be able extend cultivation 600 to 700 miles north-

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Alan L. Olmstead is the Distinguished Research Professor of Economics and a member of the Giannini Foundation of Agricultural Economics at the University of California, Davis, and serves on the board of directors of the National Bureau of Economic Research. Paul W. Rhode is a professor of economics at the University of Michigan, and a research associate of the National Bureau of Economic Research.

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[1] See Field et al. (2007, 627). More recent research suggests that the climate changes may be much greater (Sokolov et al. 2009).

ward from the current northern limit of production. Alaska is projected to become a wheat growing region.[2] Such projections necessarily must account for future technological changes, and this is an iffy proposition.

This chapter seeks to provide long-run perspective for understanding future adjustments to variation in climatic conditions. Drawing on the record from the past two centuries, we analyze how American farmers learned to produce in unfamiliar and challenging environments. We do not explicitly examine the responses to fluctuations over time in the climate at a set of fixed locations. Instead, we seek insight by investigating the behavior of settlers moving climate-sensitive production activities to new locations, locations with significantly harsher, drier, and more variable environments. These changes for the most part occurred before a modern understanding of plant genetics informed breeding activities. Our evidence says nothing directly about the ability of future farmers aided by rapid advances in plant sciences to respond to climatic changes, but the historical adjustment process does indicate that the malleability of the agricultural enterprise rendered obsolete the predictions of many past experts.

In the mid-nineteenth century, John Klippart of the Ohio State Board of Agriculture was arguably the most informed individual in the United States on wheat culture. In 1858, he published a 700-page tome detailing much of what was then known about the wheat plant and wheat farming around the world. For the age, this was a remarkable piece of scholarship. In his view, agro-climatic conditions limited the permanent commercial wheat belt to the region between the 33rd and 43rd latitudes encompassing Ohio, the southern parts of Michigan and New York, Pennsylvania, Maryland, Delaware, and Virginia. The soils in the latter three states had been largely exhausted and, without considerable investment in fertilizer, production would soon decline. Klippart was aware of the large increase in output to the west of Ohio, but he maintained that the soils and climates of Illinois, Iowa, and Wisconsin would doom those states to the haphazard production of low-quality and low-yielding spring wheat. The region beyond the 98th parallel stretching from Lake Winnipeg through eastern Nebraska to Gulf of Mexico was mostly “an unproductive desert.” Rust infestations would forever limit production in the South. Unless the country husbanded its resources, it would soon be an importer of wheat.[3] Figure 6.1 maps of Klippart’s vision of the potential long-term wheat-producing area of the United States. Klippart was so far off the mark because he failed to

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[2] See Ortiz et al. (2008).

[3] See Klippart (1860). Because of a perceived deterioration in productivity, Klippart (1860) argued that “Canada may be left out of the wheat region” (323). Lest one think that Klippart was simply an isolated alarmist, note that *Genesee Farmer* debated at length “Shall We Have to Abandon Wheat Growing in Western New York?” after the arrival of the highly-destructive wheat midge (63 [2]: 41–43).

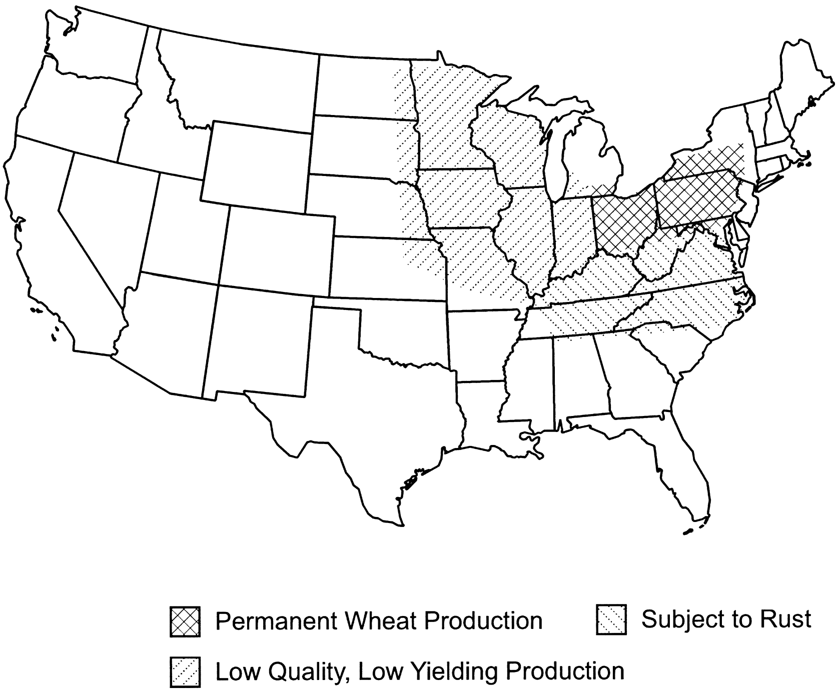

Fig. 6.1 The "potential wheat-producing area" in the United States in 1858
Source: Compiled from Klippart (1860).

anticipate the biological innovations that would transform North American wheat production.[4]

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

The movement of production into more arid regions with more variable climates was one of the hallmarks of American agricultural development. Biological innovation was a necessary condition for this expansion. Some of

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[4] Klippart was one of many prominent observers who predicted impending crises in grain production. Among the most prominent was Sir William Crookes, whose prophecies of starvation in his presidential address to the British Association for the Advancement of Science in 1898 received wide currency in the popular and scientific press. For two early twentieth century views of the land suitable for wheat, see Unstead (1912) and Baker (1928, especially 402).

America's most distinguished historians, including Fredrick Jackson Turner, Walter Prescott Webb, and their many disciples, explored the broader causes and consequences of the westward movement of agriculture. Our quantitative analysis provides a better perspective on the magnitude of the challenges that farmers confronted and offers a hint as to the flexibility of farmers to respond to future challenges. In this chapter, we analyze the changing location and climatic conditions faced by the producers of America's three great nineteenth century staples—wheat, corn, and cotton.

6.1 Wheat

From 1839 to 2002, U.S. wheat production increased nearly nineteen times, rising from roughly 85 million to 1.6 billion bushels. By 1929, the geographical center of U.S. wheat output shifted nearly 1,000 miles from near Wheeling, (West) Virginia to the Iowa/Nebraska borderlands.[5] But even more impressive than these changes in geographic center of wheat production were the shifts in the ranges of growing conditions. According to Mark Alfred Carleton, a prominent U.S. Department of Agriculture (USDA) agronomist, the regions of North America producing wheat in the early twentieth century (see figure 6.2) were as "different from each other as though they lay in different continents."[6]

Table 6.1 displays the main features of the changing geographic distribution of the U.S. wheat crop across latitudes, longitudes, elevation, annual mean temperature and precipitation, and January and July mean temperature for six selected years—1839, 1869, 1899, 1929, 1969, and 2002. The series combine county-level production data from the Census of Agriculture with fixed characteristics for each county.[7] For example, the climatic variables reflect average conditions in each county recorded over the 1941 to 1970 period by the National Oceanic and Atmospheric Administration.[8]

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

[6] See Carleton (1900, 9).

[7] The Interuniversity Consortium for Political and Social Research's (ICPSR). *Historical Demographic, Economic, and Social Data, 1790–2000,* ICPSR 2896, linked to county characteristics from the U.S. Department of Health and Human Services, the Health Resources and Services Administration, and the *Bureau of Health Professions Resource File,* ICPSR 9075. We owe a large debt to Lee Craig, Michael Haines, and Thomas Weiss for making available machine-readable crop data for 1839 to 1909. See Craig, Haines, and Weiss (2000). The information for 1969 to 2002 comes from machine-readable files from the Census of Agriculture compiled and made readily accessible by Michael Haines. We have entered the 1929 data from the U.S. Bureau of the Census (1932).

[8] See ICSPR-no. 9075 Codebook, 96. The available series include mean temperature (January, July, annual) and mean precipitation (January, July, annual), among other information. This study notes "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,

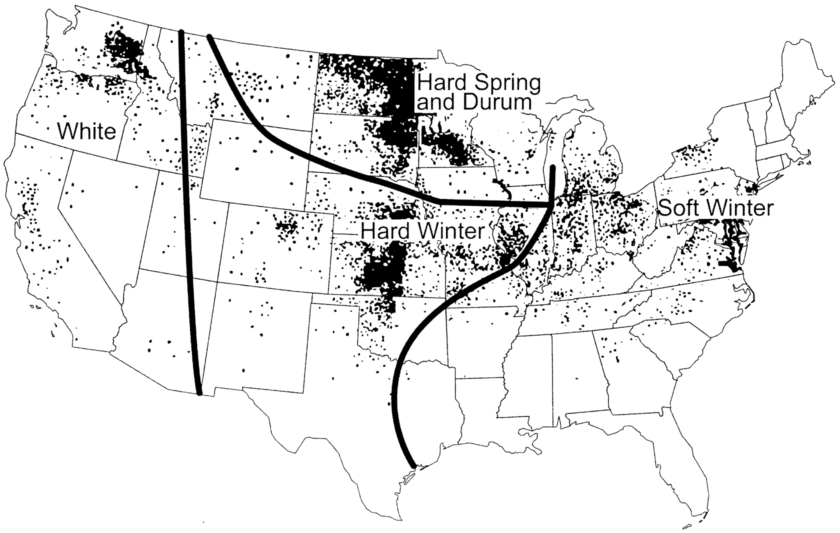

Fig. 6.2 Wheat regions
Source: Olmstead and Rhode (2008).

These variables do not capture year-to-year changes in the weather and predate the more recent secular climate changes associated with the global warming.

The top panel of table 6.1 shows the distribution of wheat production by latitude. It indicates the median is relatively constant hovering between roughly 40 and 41 degrees, but the most northern one-quarter of production (see the 75 percent line) moved nearly 6 degrees, or over 400 miles between 1839 and 2002. Over 80 percent of this movement took place by 1929, well before the Green Revolution. The next panel on longitude indicates that the median location of production shifted by more than 18 degrees (970 miles) between 1839 and 2002. The rapid movement in the most westward fringe of wheat production (track the 30 degree longitude shift in the 90 percent row) before 1899 captures the rapid expansion in the Pacific region.

The changes in the median annual and January temperatures were small. But the range of temperature conditions greatly widened, with production moving into both hotter and colder areas. The movement into more frigid zones was most pronounced. Between 1839 and 2002, the average annual temperature of the coldest 10 percent of production (the 10 percent line) dropped 7.6°F; and the January temperature, the coldest 10 percent fell

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the U.S. Weather Bureau's climate regions were used to extrapolate data from other similar climatic areas."

Table 6.1 **Distribution of U.S. wheat production**

	Percent	1839	1869	1899	1929	1969	2002
Latitude (degrees)							
South	10	35.19	37.73	36.84	36.39	35.94	35.19
	25	38.46	39.12	38.79	38.17	37.84	37.60
	50	39.95	40.56	41.17	40.50	40.31	40.84
	75	41.16	42.57	44.82	45.76	46.74	46.86
North	90	42.94	43.77	46.88	47.65	48.18	48.21
Longitude (degrees)							
East	10	76.02	77.46	81.49	84.23	87.39	86.04
	25	77.53	83.20	86.84	96.06	97.14	96.53
	50	80.65	87.89	95.69	99.33	99.36	99.00
	75	84.07	91.88	97.93	102.54	102.97	104.78
West	90	87.02	94.59	117.25	116.91	116.89	117.25
Elevation (feet)							
Lowest	10	291	291	390	603	620	392
	25	482	554	700	983	1,014	883
	50	705	770	992	1,630	1,610	1,482
	75	920	940	1,330	2,620	2,460	2,284
Highest	90	1,145	1,150	1,778	3,650	3,537	3,537
Annual precipitation (inches)							
Driest	10	33.2	28.2	18.0	13.9	13.3	11.8
	25	36.0	31.4	22.0	17.4	17.2	16.7
	50	39.0	35.6	29.2	22.0	20.8	21.0
	75	42.4	39.7	37.6	31.3	30.3	31.3
Wettest	90	47.0	43.1	42.6	38.7	38.4	42.0

Annual temperature (°F)							
Coldest	10	47.8	45.5	41.0	40.9	40.1	40.2
	25	49.7	47.9	44.7	46.2	44.3	43.7
	50	52.6	51.0	50.4	51.6	51.8	51.3
	75	55.3	54.5	55.5	55.8	56.1	56.9
Hottest	90	58.7	57.8	59.8	57.9	59.9	61.2
January temperature (°F)							
Coldest	10	23.6	16.3	7.5	8.3	6.6	5.9
	25	26.3	21.2	13.1	21.5	18.3	16.7
	50	30.1	27.1	26.8	27.8	27.8	27.8
	75	33.9	31.6	32.6	32.0	32.8	33.8
Hottest	90	38.5	38.5	38.7	36.0	37.2	40.5
July temperature (°F)							
Coldest	10	70.5	70.5	69.2	68.3	68.1	67.5
	25	71.8	71.8	71.2	70.7	70.1	70.0
	50	74.1	73.8	73.4	75.1	75.6	74.8
	75	76.2	76.2	77.0	78.7	79.3	79.5
Hottest	90	78.1	78.1	79.8	80.6	81.7	82.1

Sources: See text.

17.7°F. At the other extreme, the dividing line for the annual average temperature demarking the warmest 10 percent of production shifted 2.5°F. Between 1839 and 2002, the median elevation of production increased by 777 feet.

The most pronounced changes occurred in the distribution of production by annual precipitation. By 2002, median precipitation had fallen by 46 percent since 1839, and most production took place in a drier environment than virtually anything recorded at the earlier date. Most of the changes in almost all of the geographic and climatic variables occurred before 1929.

As wheat culture moved westward, settlers encountered climatic conditions far different from those prevailing in the eastern states or in Western Europe. This was especially true as farmers moved onto the Great Plains, which had long been considered the "Great American Desert."[9] Though the region was arid, it was not technically a desert. Still it "was long considered to be incapable of agricultural development. Gradually, however, farmers began to displace cattlemen, and by experimentation, attempted to establish a crop system."[10] The first waves of settlers moved into the High Plains during the relatively wet years of the 1880s. The efforts of these farmers, who emigrated mostly from the humid East, to cultivate the soils of the Plains without irrigation constituted:

> . . . an experiment in agriculture on a vast scale, conducted systematically and with great energy, though in ignorance or disregard of the fairly abundant data, indicating desert conditions, which up to that time the Weather Bureau had collected. Though persisted in for several years with great determination, it nevertheless ended in total failure.[11]

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

[9] See Frazier (1989, 8–9) and Webb (1959).

[10] See Goodrich et al. (1936, 207) and Olmstead and Rhode (1989, 24–25).

[11] See Johnson (1901, 681).

in North Dakota, South Dakota, and Minnesota grew hard red spring and durum wheats to the virtual exclusion of all others.[12]

Another notable breakthrough was the introduction of "Turkey" wheat, a hard red winter variety suited to Kansas, Nebraska, Oklahoma, and the surrounding region. The standard account credits German Mennonites, who migrated to the Great Plains from southern Russia, with the introduction of this strain in 1873.[13] James Malin's careful treatment describes the long process of adaptation and experimentation, with the new varieties gaining widespread acceptance only in the 1890s. In 1919, Turkey-type wheat made up about "83 percent of the wheat acreage in Nebraska, 82 percent in Kansas, 67 percent in Colorado, 69 percent in Oklahoma, and 34 percent in Texas. It . . . made up 30 percent of total wheat acreage and 99 percent of the hard winter wheat acreage in the U.S."[14] A similar story holds for the Pacific coast. The main varieties that would gain acceptance in California and the Pacific Northwest differed in nature and origin (Chile, Spain, and Australia) from those cultivated in the humid East in 1839.

As a rule, breeders and farmers were looking for varieties that improved yields, were more resistant to lodging and plant enemies, and as the wheat belt pushed westward and northward, varieties that were more tolerant of heat and drought and less subject to winterkill. Canadian experiment station data and other sources show that changes in cultural methods and varieties shortened the ripening period by about twelve days between 1885 and 1910. Given the region's harsh and variable climate, this was often the difference between success and failure.[15] The general progression in varieties allowed the North American wheat belt to push hundreds of miles northward and westward and significantly reduced the risks of crop damage everywhere.

One of the most important of the early twentieth century innovations was Marquis, a cross of Red Fife with Red Calcutta, bred in Canada by Charles Saunders. The USDA introduced and tested Marquis seed in 1912 to 1913. By 1916, Marquis was the leading variety in the northern grain belt, and by 1919, its range stretched from Washington to northern Illinois.[16]

The spread of Marquis was not an isolated case. Following extensive expeditions on the Russian plains, Carleton introduced Kubanka and several other durum varieties in 1900.[17] These hardy spring wheats proved relatively

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[12] See Olmstead and Rhode (2008, 26–27).

[13] Although the Mennonites were the most notable group of immigrants to bring new seed varieties to the United States, the practice must have been fairly common, especially in the early years of settlement. We have not seen evidence that would indicate that migrants were more receptive to new varieties released by experiment stations. See Ball (1930, 63).

[14] See Quisenberry and Reitz (1974) and Malin (1944).

[15] See Norrie (1975) and Ward (1994). Buller (1919, 175–76) credits Marquis with giving adopters about one extra week between harvest and freeze-up (which put an end to fall plowing).

[16] See Clark, Martin, and Ball (1922, 901).

[17] See Ball and Clark (1918, 3–7) and Clark and Martin (1925, 8–9).

rust resistant. By 1903, durum production, which was concentrated in Minnesota and the Dakotas, approached 7 million bushels. In 1904, the region's Fife and Bluestem crops succumbed to a rust epidemic with an estimated loss of 25 to 40 million bushels, but the durum crop was unaffected. By 1906, durum production soared to 50 million bushels.[18]

Varietal change also redefined the hard winter wheat belt. Early settlers in Kansas experimented with scores of soft winter varieties common to the eastern states.[19] 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."[20] The evidence on winterkill lends credence to this view. Data for four east-central counties for 1885 to 1890 show that over 42 percent of the planted acres were abandoned. For the decade 1911 to 1920, after the adoption of hard winter wheat, the winterkill rate in these counties averaged about 20 percent.[21] Mark Carleton also left his imprint on Kansas. In 1900, he introduced Kharkof from Russia. This hard winter wheat adapted well to the cold, dry climate in western and northern Kansas, and by 1914, it accounted for about one-half of the entire Kansas crop.[22]

Drawing on decades of research, S. C. Salmon, O. R. Mathews, and R. W. Luekel noted that for Kansas "the soft winter varieties then grown yielded no more than two-thirds as much, and the spring wheat no more than one-third or one-half as much, as the TURKEY wheat grown somewhat later."[23] In 1920, Salmon concluded that without these new varieties, "the wheat crop of Kansas today would be no more than half what it is, and the farmers of Nebraska, Montana and Iowa would have no choice but to grow spring wheat" which offered much lower yields.[24]

In addition to introducing new varieties, western farmers experimented with a range of dry-farming techniques.[25] The moisture-conserving techniques involved creating a layer of dust to retain precipitation in the soil. Between 1900 and 1930, dry farming was "responsible for a considerable advance into the semiarid region." Yet the new methods created problems, too. They quickly destroyed the humus layer and left the soil unprotected

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[18] See Carleton (1915, 404–8).

[19] See Malin (1944, 96–101).

[20] See Salmon (1920, 210).

[21] See Malin (1944, 156–59). Winterkill rates for 1911 to 1920 are calculated using data from Salmon, Mathews, and Luekel (1953, 6, 78–79). The search for varieties suitable for Kansas echoed the earlier experiences of settlers in other states. In the 1840s pioneer farmers attempted to grow winter wheat on the Wisconsin prairie. Repeated failures due to winterkill eventually forced the adoption of spring varieties. See Hibbard (1904, 125–26).

[22] See Carleton (1915, 404–8).

[23] See Salmon, Mathews, and Luekel (1953, 14).

[24] See Salmon (1920, 211–12).

[25] See Hansen and Libecap (2004a, b) and Libecap and Hansen (2002).

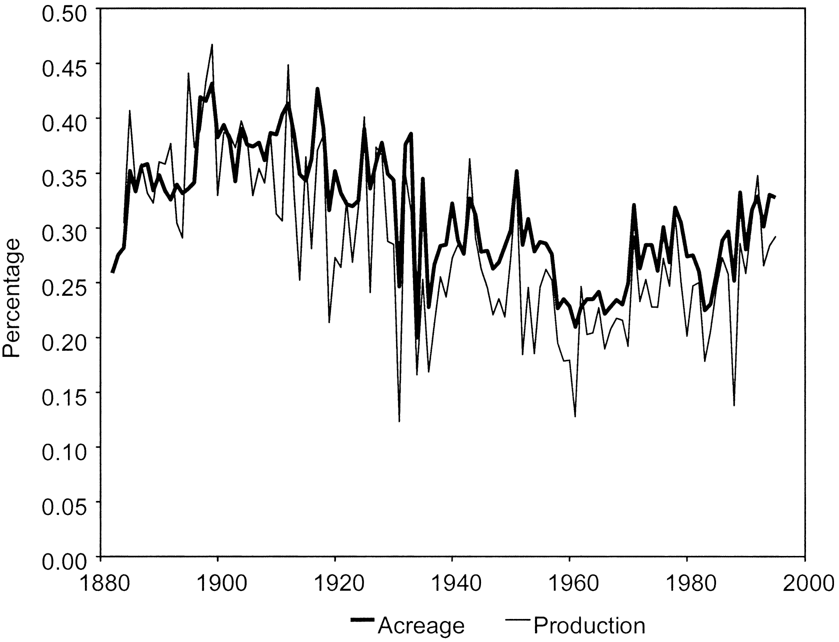

Fig. 6.3 Spring wheat as a share of U.S. output and acreage

Sources: USDA Crop Reporter (February 1908, 13); USDA Yearbook 1916 (573); USDA Yearbook 1920 (table 21); USDA Commissioner of Agriculture 1886 (410).

against the wind, leading to disastrous effects during the Dust Bowl droughts of the 1930s. "Even after 40 years of trial, a permanently successful system had not been evolved."[26] Adjustment took time.[27]

Wherever it is feasible, farmers prefer to grow winter wheat instead of spring wheat. Winter wheat generally offers higher yields and is much less subject to damage from insects and diseases. The problem is that in colder climates, winter wheat suffers high losses to winterkill. The agronomy literature commonly recognizes that the development of more hearty winter varieties that could be grown in harsher climates was a great achievement. Just how much land was affected by this fundamental change in farming practices? County-level data on spring and winter wheat production found in the agricultural censuses of 1869 and 1929 show that over this sixty-year period, winter wheat displaced spring wheat in most of Kansas, Iowa, Nebraska, and significant portions of several other states. This area accounted for almost 30 percent of U.S. wheat output in 1929.

Figure 6.3 charts the ratio of spring wheat to total wheat acreage and pro-

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[26] See Goodrich (1936, 207, 215).

[27] See Hargreaves (1957) and Hargreaves (1993).

duction in the United States. It uses the best available data from the USDA. Official revised data segregating the two types of wheat begin in 1909. Earlier unadjusted data from USDA allow us to extend the series back to the 1880s. Note the acreage share of spring wheat is typically greater than its production share, consistent with lower yields per acre for spring wheat relative to winter wheat. The spring wheat shares of acreage and output rose over the late nineteenth century as grain production moved into the northern Great Plains. This exerted a drag on overall wheat yields. The share declined subsequently, due in part to the northward shift in the spring-winter wheat line.[28] The low spring wheat shares in the 1930s are related to the Dust Bowl era droughts. As with wheat, farmers pushed the frontiers of corn and cotton production into areas previously thought unsuitable for the crops. Success in overcoming the climatic challenges required new varieties and new farming methods.

6.2 Maize

The location of U.S. corn production shifted dramatically over the late nineteenth and early twentieth centuries. Richard Steckel highlighted the significance of the photoperiodic properties of maize to explain the east-west pattern of U.S. migration during the nineteenth century.[29] His analysis demonstrated the importance of latitude in shaping the spread of corn cultivation. Corn is classified as a short-day plant. Such plants flower after the number of hours of daylight falls below a certain maximum threshold. For corn, the shortening days in the latter part of summer trigger flowering. Long-day plants such as wheat and small grains, by way of contrast, time their flowering to occur after the number of hours of daylight rises above a certain minimum. Steckel further observes that "Long-day or short-day plants that are grown outside their latitude of adaptation mature too early or too late for optimal performance."[30]

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

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[28] These long-run movements inform the debate between Fisher-Temin, Higgs, and Page over the share of the spring crop in U.S. wheat production. See Fisher and Temin (1970); Higgs (1971, 101–2); Fisher and Temin (1971, 102–3); Page (1974, 110–14); and Fisher and Temin (1974, 114–15).

[29] See Steckel (1983).

[30] See Steckel (1983, 20).

of the yield of seeds adapted to Champaign."[31] Here is solid evidence of the importance of matching corn varieties to geoclimatic conditions. For corn, north-south variations mattered significantly, but east-west variations (within the range Steckel considers) were relatively minor.

Steckel argued that pioneering farmers learned that their seed corn was adapted to the seasonal daylight conditions of their own latitude. When moving to new areas of settlement, they "probably took their own supplies of seed grain." Thus, they would be disinclined to change latitudes significantly for fear that their seeds would generate substantially lower yields. "Farmers who went too far north or south had poor yields and sent relatively unfavorable reports back to the community from which they left."[32] Although westward settlement occurred across a broad front, for many it involved movement along an east-west line.

Table 6.2 replicates the previous exercise by showing the changing distribution of U.S. corn production by location and climatic conditions. Again, it is important to recall the corn crop expanded tremendously after 1839. The crop in 2002 was about twenty-three times larger than in 1839.

The panel on longitude captures the movement in corn production—the median location shifted by about 8 degrees between 1839 and 2002. But there was also a shift in median latitude of 3.6 degrees, or roughly 250 miles to the north. In addition, the range of latitudes and climatic conditions where corn was grown widened considerably. The median annual temperature under which corn was grown fell by over 6°F from 56.3° in 1839 to 49.9° in 2002. (This is of the same magnitude but in the opposite direction of the change that the Intergovernmental Panel on Climate Change [IPCC] predicts will occur in the grain growing parts of North America over the next century.) Median annual precipitation fell by 11.5 inches, from 43.9 inches in 1839 to 32.4 inches in 2002. Median elevation rose by 370 feet. As with wheat, the bulk of the changes in location and climate occurred by 1929. This was before the widespread diffusion of hybrid corn.

The movement of corn production to drier and colder environments required biological innovation. M. L. Bowman and B. W. Crossley observed in 1908 that "the cultivation of corn has been gradually extended northward in the United States. Today this cereal is grown successfully, where twenty-five years ago its cultivation was impossible."[33] It is possible to identify specific breakthroughs that facilitated the shift of the Corn Belt several hundred miles to the north. Of special significance was the work of Andrew Boss, C. P. Bull, and Willet Hays at the University of Minnesota who developed Yellow Dent Minnesota No. 13 and Yellow Dent Minnesota No. 23: "These varieties had remarkable early ripening properties that reduced the ripening

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[31] See Steckel (1983, 22).

[32] See Steckel (1983, 23).

[33] See Bowman and Crossley (1908, 90).

Table 6.2 **Distribution of U.S. maize production**

	Percent	1839	1869	1899	1929	1969	2002
Latitude (degrees)							
South	10	33.31	34.21	34.71	34.40	38.13	37.79
	25	35.34	37.20	38.06	38.00	39.80	40.04
	50	37.78	39.51	40.10	40.48	41.02	41.38
	75	39.54	40.79	41.36	41.95	42.41	43.07
North	90	40.58	42.02	42.63	43.29	43.66	44.42
Longitude (degrees)							
East	10	76.70	77.62	82.64	83.00	83.47	85.70
	25	80.37	83.45	86.50	87.31	87.36	88.92
	50	84.54	87.80	90.75	92.05	90.47	92.68
	75	87.29	91.06	95.36	95.86	94.92	95.97
West	90	90.12	94.02	97.25	97.86	97.25	98.73
Elevation (feet)							
Lowest	10	103	255	390	375	464	520
	25	385	482	603	620	640	689
	50	590	695	819	870	833	960
	75	811	880	1,110	1,200	1,160	1,250
Highest	90	1,010	1,055	1,401	1,615	1,494	1,841
Annual precipitation (inches)							
Driest	10	36.9	33.3	27.9	25.1	25.6	22.1
	25	39.6	35.6	32.0	29.8	29.8	27.0
	50	43.9	39.0	36.0	34.8	34.5	32.4
	75	49.4	44.5	40.3	40.4	37.8	36.5
Wettest	90	53.3	50.3	47.3	48.4	42.3	40.5

Annual temperature (°F)							
Coldest	10	50.9	48.7	47.7	46.4	45.4	44.5
	25	53.3	50.9	50.0	48.9	48.1	46.7
	50	56.3	53.6	52.5	51.5	50.7	49.9
	75	60.0	57.3	56.1	56.1	52.8	52.5
Hottest	90	63.3	61.9	61.4	61.8	56.2	56.1
January temperature (°F)							
Coldest	10	26.7	21.5	18.8	16.3	14.7	12.9
	25	30.1	25.6	22.6	20.4	19.2	17.0
	50	35.1	29.6	26.9	26.2	23.9	22.7
	75	40.6	35.7	32.9	33.4	28.0	27.4
Hottest	90	45.4	43.0	41.7	42.4	33.6	33.2
July temperature (°F)							
Coldest	10	73.0	72.3	72.4	72.4	71.9	71.4
	25	75.1	74.2	74.1	73.9	73.0	72.6
	50	77.1	76.0	75.9	75.5	74.8	74.4
	75	79.0	78.2	78.2	77.8	76.3	76.3
Hottest	90	80.4	80.1	80.7	80.6	78.0	78.2

Sources: See text.

time from 120 to 125 days to about 90 days (for No. 23). These and other early ripening varieties also allowed farmers in the Canadian plains to grow corn for ensilage."[34]

According to Andrew Boss and George Pond, "the development of early-maturing varieties of corn combined with adapted hybrid varieties, and improved cultural practices are steadily drawing the Corn Belt northward and westward into the Spring Wheat area. Accompanying this movement has been a steady increase in cattle and hog production in the area which furnished the chief outlet for the corn crop."[35] Minnesota No. 13 was a potent factor in pushing corn grown for grain fifty miles northward in a single decade.[36] Between 1869 and 1929, the corn-wheat frontier moved about 400 miles at some longitudes. An enormous area including most of Minnesota, South Dakota, and Nebraska shifted from the wheat belt to the Corn Belt; these shifts would not have been possible without researchers developing earlier maturing varieties.

6.3 Cotton

Cotton, the country's third major nineteenth century staple crop, also required extensive adaptation as its culture spread across the American South and Southwest. According to J. O. Ware, a leading USDA cotton expert, the varieties that became the basis for the South's development were a distinctly "Dixie product": "Although the stocks of the species were brought from elsewhere, new types, through [a] series of adaptational changes, formed this distinctive group the final characteristics of which are a product of the cotton belt of the United States."[37] This process of molding cotton was repeated over and over again as new varieties were introduced and as production moved into new areas. According to Ware, "The vast differences in climate and soil that obtain over the Cotton Belt undoubtedly brought about a kind of natural selection which eliminated many of the kinds that were tried, while others became adapted to the several conditions under which they were grown and selected over a period of years."[38]

Cottons cultivated in the United States belong to one of two species. Sea Island (*G. barbadense*) was grown primarily along the coasts and on the offshore islands of Georgia, South Carolina, and Florida. Sea Island produced high quality, long staple fibers (over 1¼ inches), but it was low yielding and difficult to pick. Cottons of the second and more important

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[34] See Buller (1919, 187–90).

[35] See Boss and Pond (1951, 65) and Troyer and Hendrickson (2007, 905–14).

[36] See Troyer (2004, 176) and Hays (1904, 19, 82). Minnesota No. 13 was selected over several years from local seed purchased in 1893. It was first released in 1897. A number of even earlier Dents were subsequently developed at experiment stations in Minnesota, the Dakotas, and Montana. See Will (1930, 65, 85–88, 147).

[37] See Ware (1951, 1).

[38] See Ware (1936, 659) and Handy (1896).

species (*G. hirsutum*) were commonly referred to as upland cottons because they were grown in the more variable climates away from the coast. As of the turn of the twentieth century, cotton experts grouped the upland varieties into eight general types. Most of these types could be developed to fit specific environmental and economic situations and would be ill suited for other conditions. None of these cottons were native to British North America.

Adaptation was essential for the successful cultivation of upland cotton. In its native environment in Central America, *G. hirsutum* was a frost-intolerant, perennial shrub with short-day photoperiod response. As a short-day plant, its flowering was triggered when the nights began to grow longer and cooler in the late summer or autumn. This strategy was adapted to a semitropic, semiarid environment where the rains came in the autumn. The greater variation in day length over the seasons at the higher latitudes of the American South meant that the date with the right conditions to trigger flowering occurred later in the year. This meant that many of the introduced cotton varieties either did not mature before the first frost set in or did not flower at all. Initial attempts to grow upland cotton in the areas that now constitute the United States faced severe challenges. Success depended on finding a mutation/cross or a variety with the appropriate photosensitivity characteristics. "Following generations of repeated selection, these initial stocks were molded into early maturing, photoperiod-insensitive cultivars adapted for production in the southern United States Cotton Belt."[39] Adaptation was made easier because, as John Poehlman and David Sleper note, the cotton stocks first introduced to the region "were largely mixed populations with varying amounts of cross-pollination and heterozygosity that gave them plasticity and potential for genetic change."[40]

Cotton breeders confront a number of trade-offs because improving one plant characteristic often requires sacrificing another desirable quality. Breeders strive for high yields, long staple lengths, soft and strong fibers, good spinning characteristics, ease of picking, high lint-to-seed ratios, whiteness, and more. In addition, breeders work to develop cotton varieties to match local soil and climatic conditions (especially the length of the growing season), to resist specific diseases and pests, survive high winds, and to appeal to special market niches.[41] The importance of wind resistance became

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[39] See Poehlman and Sleper (1995, 376) and Stephens (1975).

[40] See Poehlman and Sleper (1995, 376). They further note that "the adjustments were hastened by the contributions of large numbers of early cotton breeders who worked without the genetic guidelines available to cotton-breeders today."

[41] Cotton's intolerance to cold limited the geographic extent of its cultivation. A freeze (below 32°F) will kill the tissues of this subtropical plant, and even temperatures below 60°F will inhibit growth. Seven months (or, more precisely, 200 days) of frost-free weather or a latitude of 37 degrees is generally considered to set the northern limit to production in the United States. See Hake and Kerby (1996, 325). Nonetheless, there were pockets of production in selected areas of Kansas, Missouri, Illinois, Kentucky, and Virginia above the 37th parallel. See Hart (1977, 308) and U.S. Department of Agriculture (1924, 153).

more significant as cotton cultivation moved onto the Texas plains, and the incentive to develop cotton that could be picked more rapidly increased as wages rose.

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

The types known as Western Big Boll, Stormproof, and Texas Big Boll cotton were noted for two characteristics. They were resistant to shedding or breaking in high winds, and they were relatively easy to pick because of their large bolls. Whereas the Eastern Big Boll cottons likely evolved from a Mexican variety imported in the 1850s by a Georgia planter named Wyche via Algeria, Texas Big Boll cotton likely evolved out of varieties imported directly from the dry plains of northern Mexico. The process of selection was similar in both regions. "Under the conditions of the great climatic change, pronounced environmental shock was effective in breaking up or isolating favorable responding genotypes. These better balanced and, therefore, more fruitful forms were readily recognized by growers who would save the seed from them. In this way desirable plant habit having the necessary production characteristics for the new adaptation or ecological area in question was established."[42]

Mexican stocks imported into different parts of the South thus took on different characteristics—presumably due to different origins, but also due to breeding to fit local environmental conditions. The first Texas Stormproof variety of note was called Supak or Bohemian in honor of the German immigrant who developed the variety around 1860. Probable derivatives of this variety were Meyer and Texas Stormproof. These three varieties gained wide acceptance in Texas, and Texas Stormproof was distributed extensively across the South. In addition, these varieties provided the germplasm for breeders such as W. L. Boykin and A. D. Mebane who developed improved Western Big Boll lines. In 1869, Boykin commenced a decade-long program of carefully selecting Meyer seed from the best plants on his farm near Terrill, Texas. Around 1880, he began planting his improved Meyer amongst Moon, a long staple variety, in a quest for a favorable hybrid. To breed storm resistant cotton, Boykin attached a string with a one pound weight to the

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[42] See Ware (1951, 83).

tip of the locks and then held up the boll by the slender stock holding the fruit. He only selected seeds from bolls with stocks that didn't break under the pressure. Boykin's cotton was similar in appearance to Meyer, easy to pick, and exceptionally storm resistant. It had a high seed-to-lint ratio with a lint length of greater than one inch.

Mebane began studying cotton near Lockhart, Texas in the mid-1870s. Over the next quarter century, he bred cotton in pursuit of a number of characteristics, including storm and drought resistance, higher lint ratios and yields, and larger easy-to-pick bolls. He succeeded in most of these areas and in the process changed his cotton's appearance, creating a stocky and compact plant that would not whip around in the wind. The high cotton so prized in the Mississippi Delta was a detriment in the windswept plains. When the boll weevil entered Texas, Mebane's variety became especially important because it was early to mature. Its success in weevil-infested areas led Seaman A. Knapp to name it "Triumph." Breeders created many other Western Big Boll varieties in the pre-World War II era. Much of this effort focused on satisfying the critical need for early varieties.[43] The early twentieth century was a challenging period for cotton producers. The boll weevil, which entered the country around 1892, spread across the traditional Cotton South as a "wave of evil."[44] The pest invasion caused a wholesale transition in the traditional cotton belt to earlier maturing cottons. Among the additional consequences were the push of cotton culture onto the High Plains of the Texas and Oklahoma and the introduction of the crop into New Mexico, Arizona, and California. These environments were far drier and hotter than those found in the traditional Cotton South. Adaption involved finding new cotton varieties and developing new growing practices.

In the early twentieth century, USDA scientists scoured Mexico and Guatemala for new varieties. In June 1906, O. F. Cook stumbled upon a single plant growing by the roadside in eastern Chiapas that had a longer and denser fiber than any Big Boll cottons then grown in the United States. Cook deduced from observing local cottons and interviewing farmers that the prized cotton was not cultivated in the immediate area, but because of heavy rains, failed to discover its exact origins. Adding to the problem, the seeds that Cook had extracted from his one plant rotted due to the humid weather. In December 1906, G. N. Collins and C. B. Doyle carried on the quest to find the home of Cook's chance discovery. They tracked the probable home to the village of Acala, where they acquired seeds for trials in the United States. Beginning in 1907, the laborious process of planting and repeatedly selecting the best plants ensued. Throughout this process, breeders worked to adapt strains for specific areas. Although growers across the West adopted

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[43] See Olmstead and Rhode (2008, chapters 4–5).

[44] See Lange, Olmstead, and Rhode (2009).

Acala varieties, the type had its greatest impact in California where it became the only variety planted on any scale for over forty years.[45]

In addition to adapting plants to meet new environments, farmers changed cultural practices as they pushed into new areas—the time of planting and harvesting, plowing and cultivating methods, and fallowing schemes were all subjects of experimentation. Irrigation was especially important for the movement of cotton into the Southwest and California. In the traditional Cotton Belt, irrigation was a rarity; in the new regions, it was nearly universal. At first, irrigation typically involved individual farmers or small collectives diverting rivers with ditches or employing pumps to tap into underground aquifers. These local efforts were supplemented by massive social overhead investments to dam large rivers and move water long distances via canals. These were all methods used to deal with climate differences as agriculturists adapted to new environments.

The responses to these new challenges are evident in table 6.3, which displays the changing distribution of cotton production by location and climatic conditions from 1839 to 2002. In the early decades of twentieth century, a significant fraction of production moved to more western lands, with hotter annual and July temperatures, lower precipitation, and higher elevations. Between 1839 and 2002, median precipitation fell by 6.4 inches; median production in 2002 occurred in areas that would have ranked in the driest 10 percent of production in 1839. The changes in the medians in the other characteristics are less dramatic. But those of the fringe, in the tails of the distribution, show what was possible. The swings were quite dramatic. In the 1960s, 1970s, 1980s, traditional cotton areas in the Southeast temporarily dropped out of production.[46] And in the mid-1970s and the 1980s, output in California doubled. A major feature in table 6.3 is the relative stability of the northern frontier of cotton production; very little production has occurred above the 37th parallel, which has long been the crop's traditional boundary. With global warming, this barrier may be breached.

6.4 Conclusion

During the nineteenth and twentieth centuries, scientists and agriculturalists created new biological technologies that allowed U.S. farmers to repeatedly push cultivation of the three major staple crops into environments previously thought too arid, too variable, and too harsh to farm. The climatic challenges that these farmers overcame in adopting crops to new areas rivaled the magnitude of the climatic changes predicted for the next hundred years in the United States.

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[45] See Collings (1926, 206–13), Turner (1981, 40–41), and Ware (1951, 116–27). The dominance of Acala in California was more a function of government policy than of the variety's superiority. See Constantine, Alston, and Smith (1994).

[46] See Hart (1977, 307–22) and Fite (1984).

Table 6.3 Distribution of U.S. cotton production

	Percent	1839	1869	1899	1929	1969	2002
Latitude (degrees)							
South	10	30.88	31.04	30.61	31.22	31.42	31.27
	25	31.69	32.04	31.78	32.39	32.79	32.73
	50	32.76	32.85	32.95	33.6	33.69	33.96
	75	33.96	34.29	34.1	34.83	35.2	35.45
North	90	34.98	35.2	35.07	35.62	36.24	36.32
Longitude (degrees)							
East	10	81.11	81.39	81.34	81.98	87.29	83.58
	25	83.55	84.49	84.78	86.52	90.19	89.68
	50	87.63	89.08	90.24	90.82	96.35	91.85
	75	91.06	91.52	95.45	96.88	102.33	102.26
West	90	91.54	94.81	97.12	99.54	118.88	118.88
Elevation (feet)							
Lowest	10	64	82	116	117	107	82
	25	130	175	201	215	194	160
	50	250	310	360	413	355	324
	75	555	476	570	745	1,403	1,405
Highest	90	700	655	770	1,470	3,254	3,370
Annual precipitation (inches)							
Driest	10	45.4	44.4	34.0	23.4	8.1	10.2
	25	48.5	47.2	43.6	36.1	17.2	17.7
	50	51.8	50.2	49.0	47.7	40.7	45.4
	75	54.4	52.8	52.2	51.4	50.1	50.4
Wettest	90	57.0	55.1	54.4	54.0	52.4	52.3

(*continued*)

Table 6.3 (continued)

	Percent	1839	1869	1899	1929	1969	2002
Annual temperature (°F)							
Coldest	10	60.9	60.8	61.0	60.0	59.7	58.9
	25	62.0	62.0	62.2	61.2	61.1	60.5
	50	64.1	64.1	64.1	63.4	62.7	62.3
	75	65.9	65.6	65.8	65.2	64.9	64.9
Hottest	90	66.8	66.9	67.5	66.9	70.1	67.6
January temperature (°F)							
Coldest	10	41.2	40.5	40.9	38.9	38.3	38.3
	25	44.1	43.1	43.1	40.9	40.2	39.1
	50	46.2	45.9	45.4	43.8	43.7	43.7
	75	49.2	47.8	47.8	46.8	46.8	46.9
Hottest	90	50.9	49.9	50.0	49.9	51.2	51.2
July temperature (°F)							
Coldest	10	78.9	79.0	79.0	78.9	79.2	78.9
	25	79.5	79.8	80.0	80.0	80.1	79.7
	50	80.6	81.0	81.2	81.4	81.3	80.7
	75	81.6	81.9	83.0	83.0	83.0	82.1
Hottest	90	81.9	83.0	84.5	84.6	84.8	84.3

Sources: See text.

The effects of climate change are likely to appear both in gradual terms and in episodic crises such as outbreaks of new pests and in the onset of severe droughts. This chapter bears on the historic responses to the equivalent of gradual changes. The chapter does not address related shocks that are the predicted dire consequences to agriculture of global warming, including 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. But the historical record does show that farmers were able to develop technologies to push crop production into areas previously thought unsuitable for agriculture because of the harsh climatic conditions. There is little reason to think that future technological advances and crop substitutions will not partially offset some of the problems created by global warming. Plant scientists offer a mixed view on the prospects of breeding advances to stave off the consequences of global warming. Breeders of annual crops have expressed confidence that they can employ both traditional and transgenic methods to develop varieties of maize and other crops to keep up with the gradual effects of climate change. However, their ability to deal with episodic events such as the introduction of new pests is far more problematical. The adaptation of perennial crops will be more difficult than adapting annuals in part because the breeding cycle is longer and many perennials prosper commercially only in small geoclimatic niches.[47] There will be enormous challenges to the agricultural sector associated with impending climate changes. As in the past, public and private research will be crucial in meeting the new environmental realities.

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[47] See Hest (2008) and Koski (1996, 235–39).

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