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The Red Queen and the Hard Reds: Productivity Growth in American Wheat, 1800–1940

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Standard treatments of U.S. agriculture assert that, before the 1930s, productivity growth was almost exclusively the result of mechanization rather than biological innovations. This article shows that U.S. wheat production witnessed wholesale changes in varieties and cultural practices during the nineteenth and early twentieth centuries. Without these changes, vast expanses of the wheat belt could not have sustained commercial production and yields everywhere would have plummeted due to the increasing severity of insects, diseases, and weeds. Revised estimates of Parker and Klein's productivity calculations indicate that biological innovations contributed roughly half of labor-productivity growth between 1839 and 1909.

Deciphering the mysteries of U.S. productivity growth has been one of the major contributions of the economics profession over the past half-century. Controversy still reigns for many contemporary issues such as explaining the productivity downturn in the 1970s and measuring the impact

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of computers on recent economic performance. But for the more distant past there is widespread consensus about the productivity record of such core sectors as agriculture. According to the stylized facts, American agriculture before 1940 witnessed significant increases in labor productivity resulting from mechanization but little growth in land productivity from biological advances. As an example, Willard Cochrane argued that mechanization "was the principal, almost the exclusive, form of farm technological advance" between 1820 and 1920.[1] In his Richard T. Ely Lecture, D. Gale Johnson noted that:

> While American agriculture achieved very large labor savings during the last century, which made it possible to continue expanding the cultivated area with a declining share of the labor force, output per unit of land increased hardly at all. . . . The revolution in land productivity based on important scientific advances began very recently; its beginnings were in the 1930's with the development of hybrid corn. . . .[2]

Yujiro Hayami and Vernon Ruttan repeatedly echo this theme in their comparative analysis of international agricultural development.[3] This view is also a part of the mantra of most economic historians. It is the main lesson of William Parker and Judith Klein's classic study of labor-productivity growth in grain cultivation between 1839 and 1909, and it has become a prominent fixture in the economic-history textbooks.[4]

The existing literature would have us believe that before the development of a sophisticated understanding of genetics, biological knowledge in agriculture essentially stood still, generating little or no boost to productivity or production. This leads to the popular picture of nineteenth-century agriculture as a world of unchanging cropping patterns and cultural practices, a world where each farmer sowed grain that he himself grew and that his father grew before him, a world of a happy, organic balance between cultivators and their natural environment.[5]

Focusing on wheat, this article argues that, contrary to the conventional wisdom, the nineteenth and early twentieth centuries experienced a stream of biological innovations that rivaled the importance of mechanical changes

[1] Cochrane, *Development*, p. 200, also see p. 107. Griliches's treatment is less emphatic, but appears to lead to the same general conclusion. Griliches, "Agriculture," pp. 241–45.

[2] Johnson, "Agriculture," pp. 7–8.

[3] Hayami and Ruttan, *Agricultural Development*, p. 209.

[4] Parker and Klein, "Productivity Growth," pp. 523–82. See also Walton and Rockoff, *History*, p. 334; Ratner et al., *Evolution*, pp. 264–65; Atack and Passell, *New Economic View*, pp. 280–82; and Hughes, *American Economic History*, pp. 275–76. The theme is also standard fare in the USDA's treatment of productivity growth. Loomis and Barton, "Productivity," pp. 6–8. Historians have been more inclined to emphasize the importance of biological innovations. See, for example, Kloppenburg, "First," pp. 50–65. Although Parker is best remembered for his estimates with Judith Klein that emphasize the importance of mechanization, elsewhere he expressed a strong appreciation for the importance of biological innovations. Parker, "Productivity," pp. 180–81, and "Agriculture," pp. 369–417.

[5] See Stanelle, "Certified" for a statement of this view.

for agricultural-productivity growth.[6] These new biological technologies addressed two distinct classes of problems. First, there was a relentless campaign to discover and develop new wheat varieties and cultural methods that would allow the wheat frontier to expand into the northern prairies, the Great Plains, and the Pacific Coast states.[7] Without these land-augmenting technologies, western yields would have been significantly lower, and vast areas of the Great Plains would not have been able to sustain commercial wheat production. Second, researchers and wheat farmers made great strides in combating the growing threat of yield-sapping insects and diseases, many of which were the unintended consequences of biological globalization. With the large-scale importation of Eurasian crops to North America came hitchhikers who fed on and destroyed those crops. In the absence of vigorous efforts to maintain wheat yields in the face of evolving foreign and domestic threats, land and labor productivity would have been significantly lower.[8] Although practices were not as effective as post–World War II technologies, early farmers applied a variety of integrated pest management systems with considerable success. Building on our analysis of pre-1940 biological innovations, we take a fresh look at Parker and Klein's formal estimates of labor-productivity growth between 1839 and 1909. Our revised estimates suggest that biological innovations accounted for roughly one-half of the labor-productivity growth in this period.

CORNERSTONES OF THE CONVENTIONAL WISDOM

The lesson that biological innovations were unimportant in wheat cultivation before 1940 rests on two fundamental building blocks. The first is the time series on U.S. yields, which is graphed for the 1866–1969 period in Figure 1. The figure also includes the growth trend with a break in 1939, which maximizes the fit. Output per acre harvested was nearly constant from 1866 to 1939, growing only about 0.15 percent per annum. This amounted

[6] In the context of the international-development literature the term "biological change" encompasses nonmechanical activities that modify the growing environment. In addition to strictly biological innovations such as improved plant varieties, "biological changes" include changes in cultural practices, irrigation systems, fertilizers, and chemicals.

[7] When discussing wheat, modern agronomists have abandoned the term "variety" and adopted the term "cultivars" in its place because of the subtle distinctions as to what properly constitutes a distinct variety. Because the historical literature we cite consistently refers to "varieties," we have chosen to use the dated terminology.

[8] Several USDA economists have promoted the general view that mechanical technologies dominated biological innovations in the pre-1940 era. For example see Loomis and Barton, "Productivity," pp. 6–8. In an excellent article on biological innovation in wheat, another USDA economist, Dana Dalrymple, hits on this issue noting the "effect of some yield-increasing technologies may have been masked" by disease or other problems, but he fails to develop the implications of this insight. Instead he repeats the standard mantra that "mechanical technologies were of major importance well before biological technologies." The key point is that just because yields were relatively constant does not necessarily imply that biological innovation was of minor importance. Dalrymple, "Changes," p. 20–21.

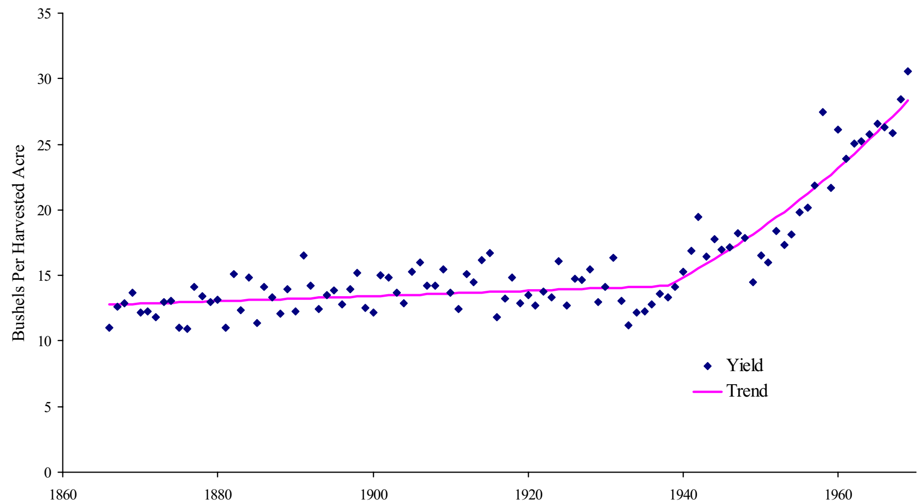

FIGURE 1
U.S. WHEAT YIELDS, 1866–1969

Source: U.S. Bureau of the Census, *Historical Statistics*, Series K 506 and 507.

to a meager 1.75-bushel-per-acre increase over nearly three-quarters of a century. After 1939 the growth rate jumped to 2.23 percent per annum, and yields virtually doubled in the course of 40 years.[9]

The second building block is research linking labor productivity to mechanization. One of the classic contributions here is Parker and Klein's 1966 NBER study of labor-productivity growth in wheat, oats, and corn over the 1839–1909 period.[10] Table 1 reproduces the core results of their analysis

[9] The use of average national yields to measure land productivity is subject to obvious conceptual difficulties. The following reasoning, for which we thank Frank Lewis, helps illustrate some of the sample selection problems involved. Suppose potential wheat land may be ranked along a scale according to its yield capacity. Given prevailing farm prices and costs, there will be a minimum yield for which it is profitable to devote the land to wheat cultivation. Land ranked below this threshold will go uncultivated and the average measured yield is based only on land above the profitable-cultivation threshold.

Now consider the effect of a yield-increasing biological innovation, which like many of those considered in this article, disproportionately increases yields on low-yielding lands. This will raise more land above the threshold, pushing out the frontier of wheat cultivation, and increase total production. Although the innovation will raise productivity on low-yielding land, it need not have a positive effect on measured yields. Indeed, if the effects of the biological innovation are limited to low-yielding lands close to the threshold, average measured yields can actually fall. Also note that other cost-reducing innovations, such as mechanization, can lower the threshold yield necessary for profitable cultivation. The frontier of cultivation will expand and measured yields will fall, even in the absence of changes in the productivity of a specific acre of land.

[10] 1909 is a shorthand; their terminal years were actually 1907–1911. Parker and Klein, "Productivity Growth," pp. 523–82. See a reconsideration of this study by the lead author, Parker, *Europe*, pp. 313–33. An earlier USDA study for the period between the First and Second World Wars reached findings similar to Parker-Klein's about the relative importance of mechanization and yield changes on labor productivity. See Hecht and Barton, "Gains in Productivity."

TABLE 1
PARKER AND KLEIN'S ANALYSIS OF LABOR-PRODUCTIVITY GROWTH IN WHEAT CULTIVATION, 1839–1909

						R3 Breakdown				
	Period	United States	R1 Northeast	R2 South	R3 West	Corn Belt	Western Dairy	Small Grain and Western Cotton	Range	California and Northwest
A: preharvest labor	1	13.6	19.1	11.3	12.4	12.4		ND	ND	ND
(hours per acre)	2	5.5	11.6	10.7	4.7	5.5	6.1	4.2	6.0	3.2
B: harvest labor	1	13.9	15.0	12.5	15.0	15.0		ND	ND	ND
(hours per acre)	2	2.4	3.0	3.0	2.3	3.0	3.0	1.8	7.5	2.0
Y: yield per acre	1	11.3	14.5	8.4	13.0	13.0		ND	ND	ND
(bushels per acre)	2	14.0	17.5	12.3	14.0	15.8	15.3	12.0	18.6	19.4
C: postharvest labor	1	0.73	0.73	0.73	0.73	0.73		ND	ND	ND
(hours per bushels)	2	0.20	0.19	0.29	0.19	0.224	0.165	0.190	0.226	0.165
W: acreage shares	1	1.00	0.26	0.46	0.28	0.282		ND	ND	ND
	2	1.00	0.04	0.09	0.88	0.207	0.098	0.477	0.015	0.081
V: output shares	1	1.00	0.33	0.34	0.32	0.324		ND	ND	ND
	2	1.00	0.05	0.08	0.88	0.235	0.108	0.408	0.02	0.108
Total labor per bushel	1	3.17	3.08	3.56	2.84	2.838		ND	ND	ND
((a+b)/y)+c	2	0.76	1.02	1.40	0.69	0.762	0.760	0.690	0.952	0.433
"Mechanization effect"		1.29								
"Yield effect"		2.68								
"Western settlement effect"		2.90								
"Combined mechanization and settlement effects"		0.84								

Notes: Period 1 is 1839; Period 2 is 1907–1911. ND means no data. For regional definitions, see the text of footnote 11. In 1839 the Corn Belt and Western Dairy are not segregated. "Mechanization Effect" measures hours per bushel using 1907–1911 labor coefficients and 1839 values of yields and regional output shares, that is A, B, C = 2; Y, V = 1; "Yield Effect" uses 1907–1911 yields and 1839 labor coefficients and regional output shares, Y = 2, A, B, C, V = 1; Western Settlement Effect" uses 1907–1911 regional output shares and 1839 labor coefficients and yields, V = 2; A, B, C, Y = 1, "Combined Mechanization and Settlement Effects" use 1907–1911 labor coefficients and regional output shares and 1839 yields A, B, C, V = 2; Y = 1.
Source: Parker and Klein, "Productivity Growth," pp. 532–35.

for wheat.[11] Overall, Parker and Klein found that wheat output per hour increased 4.17 fold over this period. In their estimation, the driving force was mechanization, which acting alone would have increased output per hour by 2.45 times. The interaction of mechanization with western expansion raised this ratio to 3.77 times (or about 90 percent of the total increase). By way of contrast, biological advances played a minor role; holding all else constant, yield changes increased labor productivity by only 18 percent. These results reinforce the general view that significant biological changes did not begin until the mid-twentieth century.

A closer look at the Parker–Klein study offers insights on two other fundamental issues: changes in land productivity and the role of western settlement in the growth of total production. Parker and Klein consider output per acre only as an indirect source of labor-productivity movements, but the yield increases are important as measures of land productivity and directly influence total factor productivity.[12] With a slight change in perspective, the information in Table 1 reinforces a common claim that western settlement moved wheat cultivation onto less productive soils. In the absence of these shifts, Parker and Klein's data suggest that 1909 yields would have been 29.8 percent higher than in 1839 and 4.3 percent higher than they actually were.[13]

[11] Parker and Klein divide the United States into three major regions: the Northeast (including PA, NJ, NY, VT, MA, NH, ME, CT, and RI), South (DE, MD, VA, WV, KY, TN, NC, SC, GA, FL, AL, MS, LA, and AR), and West (everywhere else). In their detailed analysis, they broke the West into five regions: Corn (including OH, IN, IL, IA, and MO), Dairy (MI, MN, and WI), Small Grain and Western Cotton (NE, KS, SD, ND, MT, TX, and OK), Range (NM, AZ, CO, UT, NV, and WY), and Northwest and California (ID, OR, WA, and CA).

They then estimate for each region the labor required in the preharvest, harvest, and postharvest operations; the direct requirements reflect the state of mechanization. The last operation is modeled to depend directly on output whereas the first two depend directly on acreage. To determine preharvest and harvest labor requirements per bushel, they divide by the crop yield. This is the only way that yields, embodying the state of biological knowledge, enter the calculation. Parker and Klein do not, for example, treat farmers as devoting labor to increase yields. Moreover, their approach implies that increases in yields result in less than one-for-one increases in labor productivity. After deriving the regional labor-output ratios, Parker and Klein use the region's weights in total production to obtain the U.S. average labor requirement per bushel of wheat. By substituting the direct labor requirements, yields, and regional weights for different periods, Parker and Klein decompose changes in labor productivity into the effects of (and interactions between) mechanization, biological change, and western settlement, respectively.

[12] Frank Lewis's reasoning noted previously suggests that associating changes in yields with changes in land productivity might be misguided. Lewis's skepticism is consistent with the view of S. C. Salmon, one of America's leading wheat experts. Salmon noted that "yields per acre are often used to measure or indicate technological improvements. They are reasonably good indices in countries in which acreage remains fairly constant or where the productivity of the new acreage does not materially differ from the old. They may be misleading, however, in a country such as the United States, where the acreage has greatly increased in areas where the conditions for growth are quite different. If an improvement reduces cost per acre, thereby permitting a larger expansion on less productive land, average over-all acre yields may actually be reduced." Salmon et al., "Half Century," p. 5.

[13] Note that Fisher and Temin criticized Parker and Klein for focusing exclusively on labor productivity, rather than total factor productivity. Fisher and Temin, "Regional Specialization," pp. 134–49.

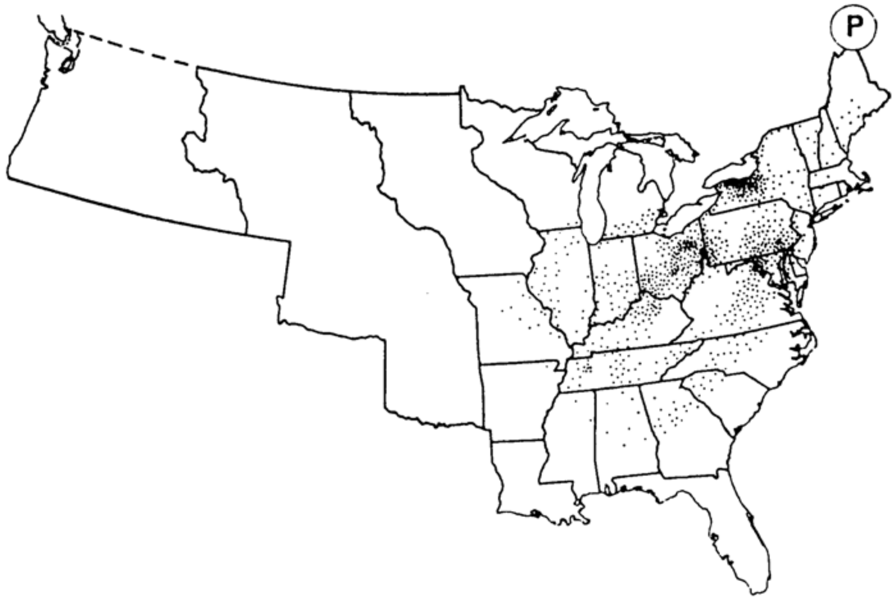

FIGURE 2A
WHEAT PRODUCTION, 1839

Note: Each dot represent 100,000 bushels.
Sources: Paullin, *Atlas,* plate 143P, used by permission.

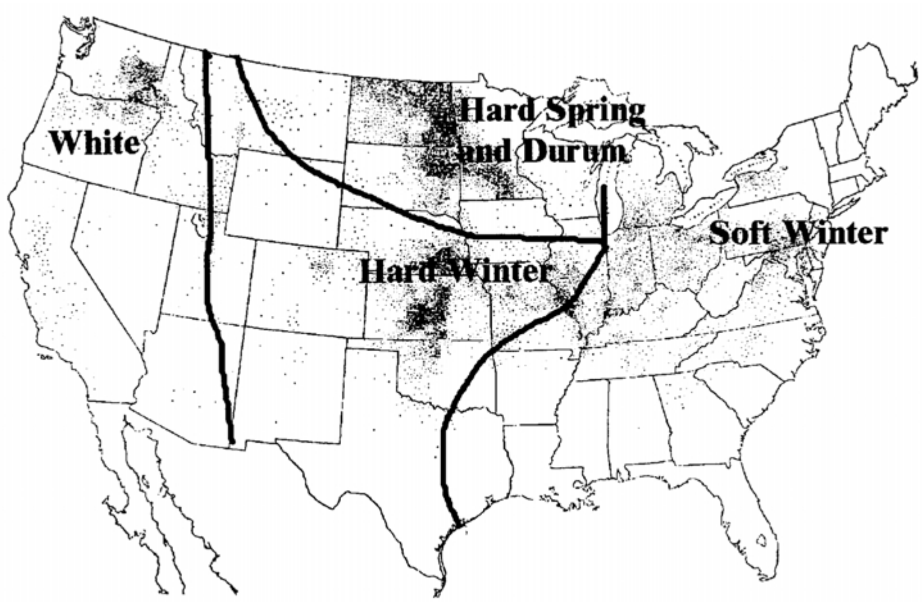

FIGURE 2B
WHEAT PRODUCTION, 1909

Note: Each dot represents 50,000 bushels.
Source: U.S. Bureau of the Census, *Thirteenth Census*, Vol. 5, plate no. 3.

Over the 1839–1909 period, U.S. wheat production increased almost eight-fold, rising from roughly 85 million to 640 million bushels.[14] The rapid growth in output was crucially dependent on the western expansion of cultivation.[15] These geographic shifts are illustrated in Figure 2, which maps the distribution of U.S. wheat output in 1839 and 1909, and in Table 2, which shows the changing geographic center of production over the same period.[16] In 1839 the center was located east of Wheeling, (West) Virginia. Cultivation was concentrated in Ohio and upstate New York; relatively little was grown as far west as Illinois. By 1909 the center of production had moved over 800 miles west to the Iowa–Nebraska borderlands. The core areas of the modern wheat belt had emerged in an area stretching from Oklahoma and Kansas in the south to the Dakotas in the north (as well as the Canadian Prairies). Another important concentration appeared in the Inland Empire of the Pacific Northwest. The western shift was so overwhelming that "new areas," not included in Parker and Klein's 1839 regions, accounted for 64 percent of 1909 output and 74 percent of the growth from 1839 to 1909. More generally, the area west of the Appalachian Mountains, which had made up less than one-half of output in 1839, provided 92 percent of output by 1909.

Figure 2, which also shows different types of wheat grown in the four major wheat regions of the United States, illustrates the significance of this shift in the locus of production. According to Mark Alfred Carleton, a leading USDA agronomist, these regions possessed such different geoclimatic conditions that "they are as different from each other as though they lay in different continents."[17] The key point for our re-evaluation of Parker and Klein is that in 1839 wheat was only extensively grown in the eastern half of just one of these four regions. In addition, by 1909 the newer regions specialized in varieties—the Hard Reds—that were completely

[14] More precisely, this was a 7.54 fold (or 2.9 percent per annum) increase, which exceeded the growth in labor productivity noted in the text. Thus, the wheat sector was continuing to absorb labor over this period.

[15] In their study of the elasticity of the U.S. wheat supply over the post-bellum period, Fisher and Temin raise a related critique of the Parker-Klein approach. Fisher and Temin note that in the presence of rising marginal costs, average productivity calculations such as Parker and Klein's are difficult to interpret. Attempting to achieve 1909 output levels under the 1839 geographic distribution would lead to sharply diminishing returns to land and require significantly greater application of labor. Fisher and Temin, "Regional Specialization," pp. 134–49.

[16] We calculated the 1839 and 1909 center from Census county-level production data and the location of the county's seat. The 1839 data are from Craig et al., "U.S. Censuses of Agriculture," and "Development." Those for 1909 data are from U.S. Bureau of the Census, *Thirteenth Census*, Vols. 6–7. The information for 1849–1899 and 1919 (mean only) is from U.S. Bureau of the Census, *Statistical Atlas*, p. 22. The county seat location data are from Sechrist, *Basic Geographic and Historic Data*. The data include only U.S. production. As a result, the changes do not capture the spread of grain cultivation onto the Canadian Prairies.

[17] Carleton, *Basis*, p. 9. The four general wheat regions shown in the lower panel of Figure 2 represent gross demarcations because each of these areas contained important sub-regions.

TABLE 2
THE CHANGING GEOGRAPHIC CENTER OF WHEAT PRODUCTION, 1839–1919

	Mean Location							Movement of Mean Location	
	Latitude			Longitude					
	deg	min	sec	deg	min	sec	Approximate Location	Decade	Miles
1839	39	30	00	80	48	00	60 miles SW of Wheeling, WV	1839–1849	81
1849	40	14	18	81	58	49	57 miles NE of Columbus, OH	1849–1859	214
1859	39	59	59	86	01	38	18 miles NE of Indianapolis, IN	1859–1869	153
1869	40	39	17	88	48	40	82 miles NE of Springfield, IL	1869–1879	89
1879	40	36	14	90	30	46	69 miles NW of Springfield, IL	1879–1889	157
1889	39	33	53	93	09	18	138 miles SE of Des Moines, IA	1889–1899	173
1899	41	39	19	94	59	23	70 miles W of Des Moines, IA	1899–1909	60
1909	42	12	18	95	53	13	48 mile SE of Sioux City, IA	1909–1919	111
1919	40	36	20	95	42	39	111 miles SE of Sioux City, IA	Total 1839–1909	809

Notes: The Total Miles of Movement between 1839 and 1909 is based on the starting and ending locations and, due to variations in the direction of movement, is less than the sum of decadal Movement of Mean Location miles.
Sources: The 1839 data are from Craig et al., U.S. Censuses of Agriculture; and Craig et al., "Development." Those for 1909 data are from U.S. Bureau of the Census, *Thirteenth Census*, Vols. 6–7. The information for 1849-1899 and 1919 (mean only) are from U.S. Bureau of the Census, *Statistical Atlas*, p. 22. The county-seat location data are from Sechrist, *Basic Geographic and Historic Data*.

different from those produced in the older areas. For the most part these varieties did not exist in the United States in 1839.[18]

This observation suggests that the Parker–Klein calculations suffer from index number problems similar to the classic "new goods" issue. As the "ND" marks for several of the western areas in Table 1 illustrate, the relevant data for many of the leading producing states in 1909 on labor requirements and yields are lacking in 1839. In their standard approach, Parker and

[18] It is useful to clarify the basic nomenclature of wheat. The primary distinction is between winter (-habit) and spring (-habit) wheats. ("Habit" is added because the distinction does not depend strictly on the growing season.) Winter-habit wheat requires a period of vernalization, that is, prolonged exposure to cold temperatures, to shift into its reproductive stage. This typically involves sowing in fall and allowing the seedlings to emerge before winter. During the cold period, the winter-habit wheat goes dormant but remains exposed to risks of winterkill. The grain is harvested in the late spring or early summer. Spring-habit wheat grows continuously without a period of vernalization. In Europe and North America, farmers in cold regions often sow spring-habit wheat shortly before the last freeze, harvesting the crop in mid- to late summer. But it is interesting to note that varieties with spring-habits were also used in areas with mild winters, such as the Mediterranean and California. There, the wheat was planted in the fall and grew without interruption. (There is a third, less important category of facultative wheat that is intermediate in cold tolerance but does not require vernalization to flower and develop grain.) Note that a longer growing season is generally associated with greater yield potential, but also involves greater exposure to weather risks, diseases, and insects.

Other important distinctions refer to the kernel's texture (soft, semi-hard, and hard) and color (white versus red). Hard wheats, which were relatively drought-resistant, outperformed soft wheats in the more arid areas. The rough-and-ready dividing line was between 30 and 35 inches of precipitation. (Salmon, "Climate," pp. 334–35.) East of the Mississippi, soft white and red wheats were prevalent whereas in the Great Plains, hard reds traditionally dominated. Durum wheat, which became popular in selected regions of the northern Great Plains after 1900, is a distinct species from common wheat, with distinct flour quality and uses.

Klein lump together all of the states from Ohio to the Pacific Coast into the "West." To address the problem of shifts within this vast, heterogeneous region, they did explore a modified productivity calculation replacing the 1909 labor requirements and yields of their "West" with those for the five Midwestern states (their "West: Corn").[19] This adjustment generated slight changes in the results, but as in the standard calculations, it misses the fundamental role that biological changes played in allowing the spread of wheat to the new lands of the West and in maintaining yields everywhere in the face of growing threats from pests and diseases.

THE INTRODUCTION OF NEW WHEAT VARIETIES

As wheat culture moved onto the northern prairies, Great Plains, and Pacific Coast, it confronted climatic conditions far different from those prevailing in the East.[20] Table 3 shows the average precipitation, the mean average high and low temperatures, and the length of the frost-free growing season at three agricultural experiment stations. These are relatively coarse indicators of the climatic conditions relevant for wheat production, but they serve to emphasize the substantial regional differences.[21] Annual data indicate that the driest year in the past 100 years at the Wooster experiment station in central Ohio was wetter than the average years at the stations in Hays, Kansas, and Dickinson, North Dakota. Furthermore, the coldest year on record in Ohio was warmer than the average year in North Dakota. As a result, the pioneers suffered repeated crop failures when they attempted to grow the standard eastern varieties under the normal conditions of the Plains except in protected river valleys.[22]

The successful spread of the crop across the vast tracts extending from the Texas Panhandle through Kansas to the Dakotas and 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). Accord-

[19] The latter sub-region included Ohio, Indiana, Illinois, Missouri, and Iowa and encompassed most of the wheat-growing areas in their 1839 "West." By this modified measure, aggregate labor productivity grew by 3.85 times, instead of the 4.17 times of their standard approach. The contribution of mechanization was lower, whereas that of yield increases was higher. But this is not a fully satisfactory solution. Parker and Klein's modified measure retained the output weights of their standard calculation, essentially assuming all of the wheat grown on the Great Plains, Pacific Coast, and other parts of the "West" were produced in the "West-Corn Belt." In fact, during the 1909 period, the "West-Corn Belt" accounted for only 23.5 percent of national output and 26.7 percent of the output of the "West" (which made up 87.9 percent of the national total). Parker and Klein, "Productivity Growth," pp. 535–39.

[20] For a classic example of the serious problems associated with finding varieties suitable for the frontier see Murray, *Valley Comes of Age*, p. 37; and Pritchett, *Red River Valley*, pp. 113, 228.

[21] For a discussion of weather effects see Cook and Veseth, *Wheat Health*, pp. 21–24.

[22] Clark and Martin, *Varietal Experiments with Hard Red Winter Wheats*, p. 1. Libecap and Hanson, "'Rain Follows the Plow,'" provides valuable insights into the problems of biological learning, public policy, and western settlement.

TABLE 3
WEATHER INDICATORS IN OLD AND NEW REGIONS

	Precipitation (inches)	Mean Low Temperature (degrees F)	Mean High Temperature (degrees F)	Frost-Free Days
Wooster, OH	36.2	39.1	58.5	155
Dickinson, ND	16.2	27.7	53.9	120
Ft. Hays, KS	22.8	40.1	67.3	170

Sources: Collins, *Ohio*, pp. 26 and 34; Goodman and Eidem, *Atlas*, p. 18; Socolofsky, *Historical Atlas*, p. 4; Midwestern Regional Climate Center, "Historical Climate Summaries"; "Dickinson Exp Stn, ND"; "Hays 1 S, KS"; "Weather Extremes"; and "Climatological Summary."

ing to the most widely accepted account, David Fife of Otonabee, Ontario, selected and increased the grain-stock from a single wheat plant grown on his farm in 1842. The original seed was included in a sample that Fife received from a Scottish source out of a cargo of winter wheat shipped from Danzig to 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 parental stock for later wheat innovations, including Marquis. At the time of the first reliable survey of wheat varieties in 1919, North Dakota, South Dakota, and Minnesota grew hard red spring and durum wheats to the virtual exclusion of all other variety classes.

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 migrating to the region from southern Russia with the introduction of this strain in 1873.[23] 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. . . ."[24] A similar story holds for the Pacific

[23] Ball, "History of American Wheat," p. 63. The Mennonites had introduced Turkey into southern Russia only in 1860. Bernhard Warkentin, one of the early Mennonite settlers in Kansas, reportedly imported 25,000 bushels of seed from Russia and had as many as 300 test plots near his home in Kansas. In 1904 black rust destroyed a large part of the soft wheat, but the new Russian wheat was hardly affected. Stucky, *Century of Russian Mennonite History*, pp. 27–30.

[24] Quisenberry and Reitz, "Turkey Wheat," pp. 98–114. Improvements in flour-milling technologies contributed to the spread of hard red wheat, thereby creating an example of the synergism of biological and mechanical innovations. Using the traditional stone-grinding methods, millers found hard red wheat yielded darker, less valuable flour than the softer white wheat varieties. The introduction of the middling purifier (to separate the bran from the flour) in 1870 and the new roller grinding process in 1878 allowed millers to make high-quality flour from the new varieties. Over this period, flour from

Coast: the main varieties grown in California and the Pacific Northwest differed in nature and origin (Chile, Spain, and Australia) from those cultivated in the humid East in 1839.

Wheat cultivation in the East was also in a constant state of flux, with many varieties being tried and abandoned, and others taking root where they proved better suited to evolving local conditions. The most notable change in the East in the mid-nineteenth century was the replacement of soft white varieties by soft reds. Leading this transition was Mediterranean, a late-sown variety introduced from Europe in 1819, which gained wide favor during the 1840s and 1850s. The field of competing varieties was large and ever changing. In 1857 the Ohio State Board of Agriculture catalogued 111 varieties (96 winter, 15 spring) grown locally in recent years, detailing the time of ripening, performance in different soils and climates, flour quality, and resistance to enemies. Of the 86 varieties that we could date, 28 percent had been introduced into Ohio within the previous five years.[25]

This evidence suggests that current rapid turnover in wheat varieties, which many contemporaries view as a product of modern science, has nineteenth-century antecedents.[26] In the past as today, new wheat varieties could be secured by introduction from other regions; selection of naturally occurring mutations and crosses; and deliberate hybridization. The balance across methods has shifted in modern times, but it is important to recall that the commercial spread of wheat varieties derived from hybridization (and subsequent selection) began before 1870.[27]

Since the days of Washington and Jefferson, the U.S. government has been active in the search for new wheat varieties. The 1854 Commissioner of Patents report notes that "a considerable share of the money appropriated by Congress for agricultural purposes has been devoted to the procurement and distribution of seeds, roots, and cuttings."[28] The report describes 14 varieties of wheat recently imported from nine countries. In 1866 the newly formed Department of Agriculture (USDA) tested 122 varieties (55 winter and 67 spring) including "nine from Glasgow, eight from the Royal Agricultural Exhibition at Vienna . . . several varieties from Germany," and a num-

hard red wheat, which had formerly sold at a substantial discount relative to that ground from white winter wheat, began to sell at a premium. Knopf, "Changes in Wheat," p. 233; and Malin, *Winter Wheat*, pp. 188–89.

[25] Ohio State Board of Agriculture, *Annual Report for 1857*, pp. 737–61. Given that there was often much confusion regarding wheat names, it is likely that some varieties were listed under different names.

[26] Johnson and Gustafson, *Grain Yields*, p. 119; Pardey et al. *Hidden Harvest,* pp. 8–12; and Dalrymple, "Changes," pp. 23–27.

[27] Large, *Advance of Fungi*, pp. 302–04. In the United States, the first wheat variety derived from hybridization is usually traced back to 1870 when Cyrus G. Pringle marketed Champaign, but Todd dates American wheat hybridization to the 1840s. Todd, *American Wheat Culturist*, pp. 40–46; and Ball, "History of American Wheat," pp. 48–71.

[28] U.S. Patent Office, *Annual Report, 1854*, pp. v and x–xiii.

ber from the Mediterranean and Black Seas.[29] Private breeders were also at work, producing a large number of superior varieties (including hybrids) during the second half of the nineteenth century. As a sign of their value, these new varieties largely displaced earlier varieties in the eastern states.[30] As a rule breeders and farmers were looking for varieties that improved yields, were more resistant to lodging (stems bent and tangled) 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 (losses due to cold weather).[31] 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, which was bred in Canada by Charles Saunders who crossed Red Fife with Red Calcutta. According to Tony Ward's analysis of Canadian experiment-station data, changes in cultural methods and varieties shortened the ripening period by 12 days between 1885 and 1910. Given the region's harsh and variable climate, this was often the difference between success and failure. Kenneth Norrie's work also emphasizes the key contribution of these biological developments to the settlement of the Canadian prairies between 1870 and 1911.[32]

The introduction of Marquis and various durum varieties to the United States illustrates the rapid spread of new varieties in the early twentieth century. The USDA introduced and tested Marquis seed in 1912/13. By 1916 Marquis was the leading variety in the northern Grain Belt.[33] This was not an isolated case. As a result of extensive exploratory campaigns on the Russian plains, Mark Alfred Carleton introduced Kubanka and several other durum varieties in 1900.[34] These varieties proved to be hardy spring wheats and, at the time, relatively rust resistant. By 1903 durum production, which was concentrated in Minnesota and the Dakotas, approached 7 million bushels. In 1904 the region's Fife and Bluestem crops succumbed to a rust

[29] U.S. Dept. of Agriculture, *Report of the Commissioner*, p. 8.

[30] Among the leading new varieties were Fultz (1862), Goldcoin (1865), Fulcaster (1886), Diehl Mediterranean (1884), and Fultzo Mediterranean (1886). Carleton, "Basis," pp. 65, 70; Clark et al., *Classification*, pp. 83–85, 135, 160; and Patterson and Allan, "Soft Wheat," pp. 36–41.

[31] The economics literature focuses on yields as a summary measure of biological improvement in wheat. But breeders and farmers were also keenly interested in a number of other economically significant characteristics unrelated to yield including milling quality, protein and gluten content, color, baking quality, and the percentage of the kernel weight that was converted to flour.

[32] Norrie, "Rate of Settlement," pp. 410–27; Ward, "Origins," pp. 864–83. Ward's regression estimates capture other effects besides the switch to Marquis. He notes, for example, that the time of ripening of Red Fife declined over the period also and that changes in cultural techniques such as employing grain drills also reduced the time of ripening. Buller, *Essays*, pp. 175–76, credits Marquis with giving adopters about one extra week between harvest and freezeup (which put an end to fall plowing).

[33] Clark et al., "Classification of American Wheat Varieties," pp. 90–91.

[34] Ball and Clark, "Experiments," pp. 3–7; and Clark et al., "Varietal Experiments with Spring Wheat," pp. 8–9.

TABLE 4
DIFFUSION OF NEW WHEAT VARIETIES IN THE HARD SPRING WHEAT STATES, 1914–1921: SHARES OF PRODUCTION BY VARIETY
(percentages)

	(1) Marquis	(2) Durum	(3) Velvet Chaff	(4) Bluestem	(5) Fife	(6) Other	(7) Total New (1) + (2)
			Three States: MN, ND, SD				
1914	4.1	11.6	20.9	44.2	15.6	3.7	15.7
1916	33.2	12.5	22.4	22.3	9.1	0.4	45.7
1917	45.0	16.5	18.8	14.1	5.0	0.7	61.5
1918	55.2	19.3	14.3	6.5	3.6	1.2	74.5
1919	56.9	23.6	10.7	5.3	2.7	0.7	80.4
1920	54.8	28.5	9.0	3.9	2.4	1.4	83.3
1921	49.8	37.6	5.8	2.9	2.3	1.6	87.4
			Four States: MN, MT, ND, SD				
1917	47.0	16.2	17.6	13.6	4.9	0.8	63.2
1918	55.2	19.2	13.1	7.9	3.5	1.1	74.4
1919	58.3	22.2	10.6	5.3	2.7	0.9	80.5
1920	57.0	26.4	8.4	4.1	2.4	1.7	83.4
1921	53.3	34.0	5.3	3.0	2.4	2.0	87.3

Source: "Statistics of Grain Crops," *USDA Yearbook of Agriculture 1921*, pp. 530–31.

epidemic with an estimated loss of 25–40 million bushels, but the durum crop was unaffected. By 1906 durum production soared to 50 million bushels.[35] The wholesale transformation of the wheat stock in the northern Great Plains in the late 1910s is displayed in Table 4. Overall, the production share of the traditional varieties such as Velvet Chaff, Bluestem, and Fife fell from 84 percent in 1914 to under 13 percent by 1921 as the new Marquis and Durum varieties took hold. These rates of diffusion are comparable with those publicized by Zvi Griliches for the spread of hybrid corn in the Midwest during the 1930s.

The national turnover of varieties is evident in USDA surveys of wheat distribution, first systematically collected in 1919 and reported thereafter roughly every five years until 1984. Using the 1919 survey together with information on the date of introduction or release of specific varieties, we can gain a clearer picture of the changing composition of the wheat varieties grown in the United States.[36] In that year, roughly 24.2 percent of U.S. wheat acreage was in hard red spring wheat, 6.4 percent in durum, 32.0 percent in hard red winter, 30.1 percent in soft red winter, and 7.1 percent in white. It is important to recall that in 1839 there was essentially no commer-

[35] As another example, in 1900 Carleton also returned from Russia with Kharkof, a hard winter wheat adapted to the cold, dry climate in western and northern Kansas. By 1914 it accounted for about one-half of the entire Kansas crop. Carleton, "Hard Wheats," pp. 404–08.

[36] Clark et al., "Classification." A variety's "vintage" is measured since first introduction. It often took a decade for new varieties to be tested on farms and begin to gain acceptance (in the case of Turkey general acceptance took over 20 years), so the mean number of years since general availability would have been much less.

TABLE 5
VINTAGE OF U.S. WHEAT VARIETIES IN 1919

Decade of Introduction	Percentage of Acreage	Decade of Introduction	Percentage of Acreage
Before 1800	0.2	1860–1869	6.7
1800–1809	0.2	1870–1879	31.6
1810–1819	3.6	1880–1889	9.7
1820–1829	0.7	1890–1899	8.7
1830–1839	1.7	1900–1909	9.8
1840–1849	1.2	1910–1919	17.0
1850–1859	2.0	Unknown	6.9

Sources: Clark et al., "Classification"; and "GrainGenes," [online database].

cial production of durum or the hard reds, which comprised 62.8 percent of the 1919 total. Table 5 provides further evidence on the age distribution of wheat varieties in 1919. Of the 133 varieties that could be dated, the acreage-weighted mean "vintage" was 1881, or less than 40 years old. The median was 1873, which corresponded to the introduction of Turkey. This is not surprising given that Turkey was the largest single type, making up almost 30 percent of total acreage. Note that even the soft red winter varieties experienced significant turnover. Their mean "vintage" was 1868. And of the top four soft red winter wheats in 1919—Fultz, Fulcaster, Mediterranean, and Poole—only Mediterranean was introduced before 1839.[37] The key results are that in 1919, well before the usual dating of the onset of the biological revolution, roughly 80 percent of U.S. wheat acreage consisted of varieties that did not exist in North America before 1873, and less than 8 percent was planted in varieties dating earlier than 1840.

Farmers in the Great Plains, Mountain states, and Pacific Coast showed a strong revealed preference for varieties different from those grown in the wheat belt of 1839. But were the advantages of the new wheats large or small? On this issue we have some evidence, albeit fragmentary. The controlled settings of the experiment station variety trials provide perhaps the best information. For example, from the late 1880s on, the stations in Minnesota and North Dakota cooperated to test hundreds of spring wheat varieties in the northern plains. Because the agronomists rapidly dropped unsuccessful varieties after one to three years, the eastern stocks rarely even appeared in these trials. Even the best of the soft spring wheat varieties that were tested, such as China Tea and Lost Nation, left officials disappointed because of the low yields and inferior quality.[38] To provide perspective, these officials estimated that soft wheats of standard grade would have to out-yield their "famous" hard wheats by five bushels per acre to overcome

[37] Clark and Quisenberry, "Distribution," p. 37.

[38] China Tea, also known as Black Tea, Siberian, Java, and Early Java was imported to New York from Switzerland around 1837. Clark et al., *Classification,* pp. 140–41. Given that it takes several years to increase the seed, the variety could not have been widely available in 1839. Thus using China Tea as the 1839 reference variety biases the case against biological innovation.

the quality differential.[39] Combining the quantity and quality differences meant that the soft wheats suffered an effective yield disadvantage relative to Red Fife of 28 to 54 percent according to tests conducted in the Red River Valley. This gap would have been far greater in the colder and drier expanses further west.[40]

These results help explain why by the early twentieth century effectively all of the wheat grown in Minnesota and the Dakotas consisted of durum or hard spring wheat varieties. Moreover, the contrasts between China Tea and Lost Nation with Red Fife, as large as they were, significantly understated the extent of technological change because by 1909 Red Fife had been largely replaced by yet superior varieties, including Bluestem and Preston, along with various durum wheats. As the 1914–1921 production data underlying Table 4 reveal (consistent with earlier experiment-station results), the durum yields were roughly one-third (32 percent) higher than Fife and the newer hard spring wheats out-yielded Fife by about 16 percent.[41] The net result is that, in the northern plains, the varieties available around World War I offered a net return (combining yield and quality differences) that about doubled what could have been earned growing the defunct varieties that had been available in the United States or Canada in 1839.[42]

The situation was similar in the hard winter wheat belt. Early settlers in Kansas experimented with scores of soft winter varieties common to the eastern states.[43] 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."[44] The evidence on winterkill lends credence to this view. Data for four east-central counties for 1885–1890 show that over 42 percent of the planted acres were abandoned. For the decade 1911–1920, after the adoption of hard winter wheat, the winterkill rate in these counties averaged about 20 percent.[45]

[39] "Grain and Forage Crops," no. 10, pp. 5–10; "Grain and Forage Crops," no. 11, pp. 1–17; and Minnesota Agricultural Experiment Station, *1894 Annual Report*, pp. 253–61.

[40] "Grain and Forage Crops," no. 10, pp. 1, 12–13.

[41] By 1940 several more generations of new varieties had become available on the northern Great Plains.

[42] This understates the advantages of the new varieties because, as we shall show, if the older varieties had been planted continuously on vast tracts, they almost surely would have become highly susceptible to diseases, vastly widening the observed yield gap.

[43] Malin, *Winter Wheat*, pp. 96–101.

[44] Salmon, "Developing Better Varieties," p. 210.

[45] Clearly, many factors could account for the decline, but both Malin and the Kansas State Board of Agriculture credit the new hard winter wheat varieties for improving the survival rate. Malin, *Winter Wheat*, pp. 156–59. Winter kill rates for 1911–1920 are calculated from Salmon, "Developing Better Varieties," pp. 78–79; and for national winterkill data see Salmon et al., "Half Century," p. 6. The approximately 20-year effort of farmers in Kansas to discover which varieties of wheat were best suited for a given region was simply a reenactment of what settlers in other regions of the country had experienced. As an example, in the 1840s pioneer farmers attempted to grow winter wheat on the Wisconsin

Drawing on decades of research, S. C. Salmon et al. 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."[46] 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.[47]

By the eve of World War I, Nebraska had emerged as the nation's fourth leading wheat producer, in large part because of the availability of winter-hardy Turkey wheat varieties. Its farmers experienced many of the same challenges as growers in Kansas and relied primarily on spring wheat until after 1900 because of the high winterkill losses suffered by the soft winter varieties.

> Some measure of the benefit derived from the general culture of TURKEY wheat in Nebraska after 1900 is afforded by comparing its average yield with that of spring wheat at the North Platte Station in western Nebraska. During the twenty-eight-year period ending in 1939, . . . winter wheat yielded on the average 20.6 bushels as compared with 14.3 for spring wheat, a gain of more than 44 per cent. At Lincoln, in eastern Nebraska, the corresponding gain for a this 31-year period is 14.2 bushels, or 96 per cent.[48]

The movement in actual statewide yields bolsters this evidence. Yields had averaged about 12.5 bushels per acre for 1870–1900, but jumped by about 40 percent to 17.5 bushels in 1900–1909. At the time scientists attributed the vast majority of this increase to the substitution of Turkey Red for spring wheats.[49]

Allen Clark and John Martin's analysis of field tests conducted across the Great Plains and in the Pacific Northwest between 1906 and the early 1920s offers further evidence that hard winter wheat outperformed soft winter varieties in yield, days to maturity, and survival rates.[50] Their summary

prairie. Repeated failures due to winterkill eventually forced the adoption of spring varieties. Hibbard, *History of Agriculture*, pp. 125–26.

[46] Salmon et al., "Half Century," p. 14.

[47] Salmon, "Developing Better Varieties," pp. 211–12. Salmon's estimates deserve our attention. He was one of America's leading agronomists and was responsible for introducing the first dwarf varieties into the United States from Japan following World War II. The most important Japanese variety was Norin 10. As further evidence of the importance of the nineteenth-century trade in plant products, one of the parents of Norin 10 was Turkey which the Japanese had imported from the United States around 1890. Quisenberry and Reitz, "Turkey Wheat," p. 110.

[48] Salmon et al., "Half Century," p. 16.

[49] Montgomery, "Wheat Breeding," pp. 4–7. Also see, Kiesselbach, "Winter Wheat," pp. 6–7, 103, and 107. The definition of Turkey Red lacks precision. There were several strains of Turkey Red, including Malakoff, Kharkov, Crimean, and Beloglina. All were Turkey-type wheats that had been adapted for Nebraska conditions.

[50] Clark and Martin, "Varietal Experiments with Hard Red Winter Wheats." The tests comparing Turkey with spring wheats and soft winter varieties referred to previously significantly understate the advantage that Turkey would have had over wheats available in 1839. In particular many of the soft

finding was that "hard red winter wheat is now the principal crop in many sections of limited rainfall, including much of Kansas and Nebraska, western Oklahoma, northeastern Colorado, Central Montana, and the drier portions of the Columbia Basin of Oregon and Washington. In these areas farming was not practiced or was exceedingly hazardous before this class of wheat was grown."[51]

An examination of the spread of wheat culture in the Pacific Northwest supports this general view. By the end of the nineteenth century the Inland Empire, comprising parts of Idaho and eastern Washington and Oregon, had emerged as a major wheat producer. In 1909 combined production in these regions rivaled that of Minnesota. The eastward march of wheat production in the northwest was dependent on a succession of ever-superior wind and drought resistant varieties, including the famous Baart and Federation wheats developed in Australia. A survey conducted in 1918/19 showed that none of the commercially important varieties grown at that time in Washington had existed in the United States in 1839 and that almost 50 percent of the state's acreage consisted of varieties that would not have been available to Washington farmers until after 1900. Due to the initiatives of W. J. Spillman, the state could boast one of the most impressive wheat research programs in the world by the beginning of the twentieth century. Spillman began crossing spring and winter varieties in 1899, and the first of his hybrids was released in 1907. "During the season of 1908 there were almost one thousand new or selected varieties growing on the Experiment Station farm."[52] Between 1911 and 1926, Spillman succeeded in hybridizing 1,240 new wheat varieties. The best of Spillman's hybrids which were chosen for distribution offered yield advantages of five to ten bushels an acre in a wide range of test conditions and rapidly gained favor.[53]

How should one interpret this enormous scientific effort, along with the broader process of farm-level experimentation that transformed wheat production in every region of the country and allowed wheat cultivation to move into vast regions that in 1839 were considered impossible to farm? The conventional wisdom's fixation on the development of hybrid corn in the 1930s as representing the beginnings of the true revolution in land productivity implies that the biological innovations in wheat discussed in this article were of little consequence. This is the assumption underlying Parker

varieties actually tested were themselves developed as hybrids between Turkey and other varieties in order to be suitable for more arid conditions.

[51] Clark and Martin, "Varietal Experiments with Hard Red Winter Wheats," p. 1. Besides Fife, another important variety grown in the northern Great Plains was Haynes Bluestem. This was a hard red spring wheat derived from an eastern semi-hard, red, winter wheat. L. H. Haynes of Fargo, ND, developed the variety through selection by 1885. The Minnesota experiment station further improved the variety, creating a pure-line variety, Minn. No. 169, by the late 1890s. Clark et al., "Classification," pp. 124–25.

[52] Elliott and Lawrence, "Some New Hybrid Wheats," p. 4.

[53] Schafer et al., "Wheat Varieties," p. 5

and Klein's estimates and, not too surprisingly, it is the conclusion that they reached. But rather than merely being the primitive ancestors to the modern era, the biological innovations that we have highlighted were an important ingredient and in many cases a necessary condition for the expansion of wheat culture beyond its 1839 boundaries.

THE CURSE OF THE RED QUEEN

In addition to the imperative to find well-adapted varieties, there was another crucial need for biological innovation. As wheat culture spread to new areas, so did the pathogens and pests that fed on wheat plants. Such problems tended to grow more severe over time because the vast expanses of continuously cropped wheat lands created an ideal breeding ground for the enemies of wheat to multiply and evolve, and because new threats repeatedly invaded from foreign lands. Wheat farmers were cursed by the Red Queen's dictum: they had to run hard just to stay in place.[54] Without significant investments in maintenance operations, grain yields would have plummeted as the plant's enemies evolved. To illustrate this problem, we start with an example drawn from D. Gale Johnson and Robert Gustafson's important work for a period when the scientific literature provides a clear sense of what transpired. In the early 1950s, black stem rust devastated the durum wheat crop of the northern plains, with yields per seeded acre shrinking from 14.5 bushels in the decade 1941–1951 to 9.7 bushels in 1952, 6.2 in 1953, and 3.0 in 1954.[55] A new race of stem rust, 15B, had evolved to overwhelm the previously resistant durum varieties. Only the introduction of new varieties allowed yields to recover, because once a wheat variety fell victim to rust, its economic value was permanently diminished.

Rusts, which typically are the most destructive diseases affecting wheat, are wind-blown fungi that attack the plant's stems and leaves, causing lodging and shriveled grain.[56] In the span of a couple of weeks stem rust could destroy what had promised to be a healthy crop. There were two fundamental ways that a wheat variety might avoid rust damage. First, it might have genetic resistance to the rust races currently in the area. Finding such varieties was a top priority. Before the modern age, this was a haphazard process, but breeders made significant progress. Second, a variety might mature before the rust did much damage (although under more ideal conditions, early maturation often compromised quality and yield). Because winter wheats ripened much earlier than did spring wheats, the former were generally less vulnerable to damage. One of the great achievements of wheat

[54] Carroll, *Through the Looking Glass*, p. 37; and Van Valen, "New Evolutionary Law," pp. 1–30.

[55] Johnson and Gustafson, *Grain Yields*, p. 120.

[56] Loegering et al., "Wheat Rusts," pp. 307–35. Stem and leaf rusts thrive in the hot, humid climates and attack wheat in most grain-growing regions of North America. Stripe rust thrives in cooler climates and in most years is limited to the Mountain and Pacific regions.

breeders before 1940 was the development of hardier winter wheats, which allowed many parts of Kansas, Nebraska, Iowa, Wisconsin, and Illinois to shift out of spring varieties around 1900.

Problems with rust were not new. As early as the 1660s, New England farmers were enacting a scenario that would be repeated thousands of times as farmers sought to match crops to their local conditions. Early introductions of English winter wheat failed in the harsh New England winters. After some trial and error, farmers succeeded in growing spring varieties. But in 1664 black stem rust appeared in Massachusetts, badly blasting the wheat crop by 1665. Attempts to substitute earlier maturing winter wheats also failed. The inability to find winter hardy, rust-resistant varieties largely explains why New England never emerged as a serious wheat-producing region.[57] The high incidence of leaf rust in the Southeastern United States is a major reason why little wheat was grown in that region despite generations of attempts. In addition, stem rust attacks forced large sections of Iowa and Texas to at least temporarily abandon wheat production in the late nineteenth century.[58]

Normal stem-rust losses are estimated at 5–10 percent of the wheat crop in the late-nineteenth and early-twentieth centuries.[59] Regional epidemics in 1878, 1904, 1914, 1916, 1923, 1925, 1935, and 1937 pushed losses much higher. The 1916 stem-rust epidemic is estimated to have destroyed about 200 million bushels in the United States (over 30 percent of the harvested crop) and 100 million bushels in Canada.[60] The emergence of vast concentrations of wheat in the Great Plains increased the breeding ground for rusts (and other enemies) and thus the frequency and severity of rust epidemics.[61] The added incidence of rust is just one reason why agronomists maintain

[57] Carrier, *Beginnings of Agriculture*, p. 147; Clay dates the arrival of the blast in New England in 1660. Clay, *History of Maine*, p. 38; Bidwell and Falconer, *History of Agriculture*, pp. 13–14; and Flint, "Progress in Agriculture," pp. 72–73.

[58] Carleton, "Cereal Rusts," pp. 13–19; and Carleton, *Basis*, pp. 11–22.

[59] Beginning in 1918 the USDA's *Plant Disease Reporter* began collecting estimates by polling plant specialists about the damage in each state or region. These estimates show national stem rust damage averaged around 3 percent over the 1919–1939 period, with peak losses of 23 percent in 1935. National leaf rust damage averaged around 2 percent, with a 9.6 percent peak in 1938. Roelfs, "Estimated Losses," summarizes these results for the period 1918–1976. Whereas others may have overestimated the losses to disease, there is good reason to think that the formal estimates seriously understate the losses. Subsequent studies suggest that it is likely that the scientists reporting the incidence of disease did not fully recognize the damage caused and tended to report only damage in excess of normal damage. As an example, Chester argues that the estimates of the losses to leaf rust for the years 1900-35 "must be regarded as gross under estimates." Instead of averaging about 1.5 percent he claims annual losses were at least 5 percent and maybe much higher. Chester, "Plant Disease Losses," pp. 189–362, especially pp. 210–12. For our needs actual losses are less important than understanding what would have happened without changing varieties and cultural methods. All plant scientists agree that without changing varieties and taking other defensive measures, losses would have been much higher than actually observed.

[60] Roelfs, "Effects of Barberry Eradication," pp. 177–81; Miller et al., "Diseases of Durum Wheat," pp. 75–83; Carleton, "Hard Wheats," pp. 407–08; and Dondlinger, *Book of Wheat*, pp. 167–68.

[61] Peterson, *Wheat*, pp. 201–04. Systematic efforts to estimate and record losses to rust only began after the epidemic of 1916. Hamilton, "Stem Rust," p. 157.

that the wheat-growing environment had seriously deteriorated by the early twentieth century.[62]

Compared to the advances after World War II, the early efforts to control rusts seem primitive. But that was not the perspective as of 1940, when E. C. Large proclaimed that the "greatest single undertaking in the history of applied Plant Pathology was to be the attack on the Rust diseases of cereals."[63] What accomplishments so excited Large? A systemic analysis of rusts in the United States dates back to the contributions of Mark Alfred Carleton in the 1890s. Carleton tested over 1,000 wheat varieties for yield, winter hardiness, rust and insect resistance, and for other qualities. The work of numerous other American scientists, along with research in Australia, Canada, and Europe, unlocked many of the mysteries of rust diseases. Aided by the rediscovery of Mendel's laws around 1900 and the publication of Johannsen's pure-line theory in 1901, this research accelerated the development of rust-resistant hybrids.[64]

There is clear evidence that farmers and wheat breeders were systematically developing and adopting more rust-resistant and earlier maturing varieties. For its day, Red Fife, which gained such favor in the northern Great Plains, had excellent rust-resistant qualities and was early ripening. Early Manitoba wheat farmers noted that Fife matured ten days earlier than the Prairie Du Chien variety that it replaced.[65] Marquis, which followed Red Fife, further cut the ripening period by seven to ten days, thereby providing significant rust protection. Kubanka proved remarkably resistant to the epidemic of 1904 that hammered the Bluestem and Fife crops.[66] When rusts evolved to attack Kubanka, it was replaced by Mindan (1918), which in turn was replaced in 1943 by the Carleton and Stewart varieties. At the time of their release these two varieties were highly resistant to the prevailing stem-rust races. They maintained their resistance until race 15B suddenly made them obsolete.[67] A similar progression took place in the hard winter wheat belt because the new Turkey wheats that became the dominant variety by 1900 also had excellent rust resistant qualities when first introduced. Subsequent releases were all chosen in large part for their rust resistance and because previously resistant varieties had come under attack.[68] The successive changes in varieties that began in the early colonial period were neither

[62] "Stem and leaf rust, foot rots, scab, and most other diseases appear to have been relatively unimportant in comparison with later periods. . . ." Salmon et al., "Half Century," p. 16.

[63] Large, *Advance of Fungi*, p. 292.

[64] Large, *Advance of Fungi*, pp. 292–312; and Salmon et al., "Half Century," pp. 113–14. For a treatment of the early history of rust research see Bushnell and Roelfs, *Cereal Rusts*, pp. 3–38.

[65] It probably had direct resistance also because when it was first selected '"it proved at harvest to be entirely free from rust, when all wheat in the neighborhood was badly rusted.'" Carleton, "Hard Wheats," p. 393.

[66] Carleton, "Hard Wheats," pp. 407–08.

[67] Miller et al., *Diseases of Durum Wheat*, pp. 69–92.

[68] Cox et al., "Genetic Improvement," pp. 756–60. Kanred (1917) ranked first out of 150 varieties tested for resistance to stem and leaf rust. Salmon, "Developing Better Varieties," pp. 214 and 228.

random nor haphazard. Rather the process led to a progression of ever-superior varieties, given the unstable disease environment. By the end of the nineteenth century researchers were playing an increasingly prominent role in the identification, creation, and diffusion of new varieties. In addition, the rapid rates of diffusion testify to the economic value of the new releases. Without this continuous process of technological replacement there is absolutely no reason to believe that wheat yields would have remained at observed historical levels.

A better understanding of the stem-rust life cycle allowed farmers and scientists to attack its breeding ground in barberry bushes.[69] In 1660 farmers in Rouen, France observed that wheat growing near barberry bushes was more apt to be damaged by stem rust and took steps to tear out the bushes. In the mid-eighteenth century Connecticut, Massachusetts, and Rhode Island all enacted measures against the barberry. In 1865 Anton De Bary scientifically demonstrated the role of barberry bushes as a host. Following the 1916 epidemic, the USDA launched a crusade to eradicate barberry bushes in 13 North Central states, resulting in the destruction of about 340 million bushes by 1950.[70] The eradication program delayed the disease's onset by about ten days and, by removing the site of the rust's sexual reproduction, significantly slowed the evolution of new destructive races.[71]

In addition to rusts, various smut fungi did great damage to wheat throughout North America. Stinking smut (or bunt) was the most destructive. "In a ripe but bunted ear of wheat the grains were swollen and black, still whole, but with all their inner substance transformed into a pulverulent mass."[72] Milder cases damaged the grain and lowered its value. In 1908 Peter Tracy Dondlinger noted that "formerly at least one-fifth of the cereal crops was annually destroyed by smut."[73] In addition, Hans Gussow and Ibra Conners observed that '"previous to 1900 bunt was alarmingly serious and threatened to be a limiting factor in wheat production"' in southern Canada.[74] Even if Dondlinger's figure is an exaggeration, both these accounts suggest that the damage from smut was declining by the turn of the cen-

[69] Not only did the barberry provide a home for the stem rust to carry over and multiply, the rust passed through its sexual recombination stage on the barberry. Thus, the bush was the breeding ground where rusts mutated and hybridized to develop new races.

[70] Ball, "History of American Wheat," pp. 48–71; Hamilton, "Stem Rust," pp. 156–64; Large, *Advance of Fungi*, pp. 121–46; Elwood et al., *Changes in Technology*," p. 80; and Salmon et al., "Half Century," p. 123.

[71] The rust spores can migrate over vast areas. But now new races have to migrate from Texas and Mexico, or from barberry bushes still remaining in mountainous regions. Roelfs, "Effects of Barberry Eradication," pp. 177–81; Campbell and Long, "Campaign to Eradicate," pp. 20–31; Robert Webster, interview by author, Davis, California, 27 May 2000.

[72] Large, *Advance of Fungi*, p. 70.

[73] Dondlinger, *Book of Wheat*, p. 162.

[74] As reported in Salmon et al., "Half Century," p. 16. Salmon et al. also discuss the rise of the bunt problem in the Pacific Northwest after 1900. "Nowhere in the United States and probably nowhere in the world has bunt been so serious or so difficult to control." Salmon et al., "Half Century," p. 84.

tury.[75] This was a direct result of scientific advances and farmer education. In an exhaustive series of experiments in the mid-1700s, Mathieu Tillet of France proved smut was a seed-borne disease and developed a number of treatments. Other researchers built on this discovery, leading to increasingly effective chemicals. In the nineteenth century, many American farmers soaked seeds in hot water to control loose smut and employed lime and copper sulfate solutions to fight stinking smut. By 1900 cheaper formaldehyde solutions became available and by the early 1920s mercury solutions and carbon carbonates dusts came on the market. There were still losses to smut, but they were far lower than before.[76]

Insects represented another arrow in the Red Queen's quiver. The Hessian fly, whose maggots sucked the sap from young plants, was the most destructive of the scores of insects that attack wheat. Its spread reduced yields and led to wholesale changes in the varieties planted and in cultural practices. The conventional wisdom asserts that the Hessian fly entered the United States at Long Island in 1776 in the straw of Hessian mercenaries. From New York, it spread into Pennsylvania in 1786, swept across the Alleghenies by 1797, hit Ohio by the mid-1820s, Illinois by 1844, Kansas by 1871, and reached the Pacific Coast in 1884. The new scourge, appropriately named *Cecidomyia destructor*, shifted American wheat farmers onto a significantly lower production possibility frontier.[77]

By carefully studying the fly's behavior, farmers gradually learned that they could reduce the damage by sowing winter wheat late (or for spring wheat, early) and by better cleaning their fields to reduce the carry-over of the fly population. Planting late delayed the harvest, increasing the danger from rust, but most farmers were willing to take this risk. Across the Mid-Atlantic region, farmers shifted the date of planting from the second half of August to late September or early October.[78] The fly also induced a search for new varieties that had stronger stocks to resist the maggots or that could be sown late. By far the most important biological innovation was the introduction of Mediterranean wheat from Europe in 1819.[79] This variety proved suitable for late planting and gained wide favor by the 1840s and 1850s.

[75] Dondlinger's estimate may be credible because bunt losses in modern tests with untreated seeds often exceeded 20 percent. Charles Schaller, interview by author, Davis, California, 25 April 2000.

[76] Large, *Advance of Fungi*, pp.70–82; Salmon et al., "Half Century," pp. 125–26; Freeman and Stakman, "Smuts of Grain Crops," pp. 33–64; and Boss et al., "Seed Grain," pp. 370–79.

[77] Although 1776 is the widely accepted date of entry, Fletcher asserts that the Hessian fly was in New York and New Jersey before the revolution. Fletcher, *Pennsylvania Agriculture*, p. 147.

Headlee and Parker, "Hessian Fly," p. 88; Marlatt, "Principal Insect Enemies," p. 14; Webster, "Hessian Fly," pp. 259–60. Other sources offer slightly different chronologies, but the previous account gives a general picture of its spread. There are several strains of the Hessian fly and later treatments often focus on *Mayetiola destructor*. Dahms, "Insects Attacking Wheat," pp. 428–31.

[78] Headlee and Parker, "Hessian Fly," p. 113; Bidwell and Falconer, *History of Agriculture*, p. 96; and Schmidt, *Agriculture in New Jersey*, p. 92.

[79] As is often the case there are conflicting stories as to this wheat's origin. Klose, *America's Crop Heritage*, p. 66; Ohio State Board of Agriculture, *Annual Report, 1857*, pp. 700–01; and Fletcher, *Pennsylvania Agriculture*, p. 148.

Just when American farmers were learning to live with the Hessian fly, a new scourge appeared. What the nineteenth-century literature called the grain midge first entered Vermont from Canada in the 1820s. This one insect had such a profound effect that the 1860 Census of Agriculture devoted more attention to it than to the mechanical reaper. The Census traced the midge's path of devastation across New York, beginning in the 1830s, as one county after another fell victim. In 1854 the New York State Agricultural Society estimated that the midge destroyed over 40 percent of the state's wheat crop.[80] The damage reached its zenith when the midge entered the fertile Genesee Valley. "In 1856 it destroyed from one-half to two-thirds of the crop on the uplands, and nearly all on the flats. In 1857 it was still worse, taking over two-thirds of the crop." The midge also wreaked havoc throughout New England and Pennsylvania.[81] The Census blamed the midge for most of the 44 percent decline of the New York wheat crop between 1849 and 1859, as "spring crops and winter barley took the place of wheat . . . ."[82]

Initially farmers "knew little of the habits of this minute insect, and were unable to offer it any resistance."[83] But once again they adjusted their cultural practices to survive the midge. At first there was a widespread shift from winter to spring wheats, which even if successful in avoiding the insect, offered significantly lower yields than the pre-midge winter varieties. Farmers faced a dilemma because the key to fighting the Hessian fly was to delay planting winter wheat, but the trick with the midge was to harvest as early as possible. All else equal, this required planting earlier. Thus the arrival of the midge further constricted the available options by creating smaller windows within which planting and harvesting had to take place. In New York the sowing date which had been pushed from August to late September or early October because of the Hessian fly, now had to be recalibrated to the first three weeks of September because of the midge.[84]

Experience with midge infestations showed that "'the injury has been almost entirely confined to the high quality 'white' varieties, the Mediterranean escaping altogether.'"[85] By the 1850s Mediterranean had become the

[80] Calculated from data in Bidwell and Falconer, *History of Agriculture*, pp. 323 and 333.

[81] U.S. Census Office. *Agriculture*, p. xxxiv.

[82] U.S. Census Office. *Agriculture*, pp. xxxi–xlv; quote from p. xxxiii; According to Hedrick, the timing of the demise of eastern New York as the "Granary of the Country" was largely due to the impact of the two pests, noting that they "had become so destructive that in all eastern New York wheat growing became unprofitable, and almost ceased to exist." Hedrick, *History of Agriculture*, pp. 332–35. Although most accounts date the entry of the midge from Canada in the early 1820s, Hind notes that it first appeared in northern Vermont and was not recorded in Canada until 1828/29. The destruction in Canada appears to have rivaled that in the United States, leading to the abandonment of wheat growing in many areas. Hind, *Essay*, pp. 75–101, and Hind, "Agricultural History," pp. 55–56.

[83] U.S. Census Office. *Agriculture*, p. xxxv.

[84] U.S. Census Office. *Agriculture*, pp. xl, xxxv; Bidwell and Falconer, *History of Agriculture*, p. 239. In fact, moving to an earlier planting date might allow for a slightly earlier harvest, but it was more important to find earlier ripening varieties.

[85] U.S. Census Office. *Agriculture*, p. xxxiv.

most common variety in the United States even though its flour quality and yield (in the absence of insects) were inferior to many abandoned varieties.[86] Although the 1860 Census called the midge the "greatest of all pests which has infested the wheat-crop," adjustments in cultural practices, including plowing deep, burning the chaff from infected fields and rotating crops, soon demoted it to a lesser status.

The battle against the Hessian fly intensified as countless farmers and researchers investigated the fly's behavior and tested cultural practices and wheat varieties to limit its damage. Out of necessity farmers adopted so-called fly-safe varieties that allowed for late planting and, gradually, researchers publicized "fly-safe" dates for every nook and cranny that grew wheat. The recommended dates varied by about two months with latitude, longitude, elevation, soil conditions, rainfall, and wheat varieties. As noted previously, the planting decision involved a delicate balancing of several threats, but as wheat culture moved onto the Great Plains the problem became even more difficult. Planting late to avoid the fly made the crop more susceptible to winterkill and reduced yield potential because the root system had less time to develop. Delaying the harvest exposed the crop to heat, drought, grasshoppers, and other enemies.[87] As a 1923 Kansas report noted, "the proper time of seeding must be determined for each locality by experimental sowings extending over a period of years."[88] Preventive measures had a collective dimension because the benefits of destroying volunteer wheat and cleaning infected fields of stubble were spread throughout the neighborhood.

Despite considerable precautions, there were local fly outbreaks every year and serious regional infestations roughly every five to six years. As examples, in 1900 over one-half of wheat acreage in Ohio and Indiana was abandoned due to fly damage and yields on the harvested land fell by about 60 percent. The following year the fly destroyed over half of New York's wheat crop. Kansas experienced six serious outbreaks between 1884 and 1913 with losses peaking at about 27 percent of the crop.[89] Damage tended to be more serious with unseasonably warm falls, in wet years, and in years with large volunteer crops. Nationally, estimates of annual Hessian fly losses around 1900 hover at 10 percent of the wheat crop.[90] In 1938 USDA

[86] Ohio State Board of Agriculture. *Annual Report, 1857*, p. 685; and U.S. Patent Office, *Annual Report. Agriculture*, vols. 1847–1854.

[87] However, delaying the planting date for winter wheat could markedly limit the chances for a buildup of other pests, including the greenbug, the Russian wheat aphid, aphid vectors of barley yellow dwarf virus, and the curl mite vector of wheat streak mosaic virus. Cook and Veseth, *Wheat Health*, p. 84.

[88] McColloch, "Hessian Fly," p. 80.

[89] Marlatt, "Annual Losses," pp. 461–74. For a small sample of the studies conducted and for estimates of state losses in bad years see: Roberts et al., *Hessian Fly*; Webster, *Hessian Fly*; Headlee and Parker, *Hessian Fly*, p. 113; and McColloch, *Hessian Fly*.

[90] Marlatt, *Principal Insect Enemies*, p. 13. Numerous other sources place the actual losses in this general magnitude ranging between \$50 and \$100 million. Dondlinger asserts that 10 percent is a lower-bound estimate. Dondlinger, *Book of Wheat*, pp. 172–73. The direct estimates of losses to the

entomologist J. A. Hyslop noted the "general adoption, throughout the greater part of the regions infested by the hessian fly, of the practice of planting wheat after the fly-free date has materially reduced" the losses from 6.0 percent of the crop over the 1923–1927 period to about 2.2 percent over the 1928–1935 period.[91]

What if the conventional wisdom (proclaiming a dearth of biological innovations) that underlies Parker and Klein's formal productivity estimates were correct, and farmers had made no changes to combat the fly? Numerous accounts from the late eighteenth and early nineteenth centuries tell us that farmers who did not adjust simply lost their crops.[92] For later years, experiment station investigations repeatedly showed that moving the planting date a week or two earlier typically led to heavy losses. One Kansas study is particularly noteworthy because it was based on the experiences of a large number of real farms. It showed a close correlation between regional fly losses and the proportion of the wheat sown before the fly-free date.[93] Another Kansas study reported what happened in the absence of normal precautions such as planting early and destroying volunteer wheat. In a controlled test, the wheat on the improperly managed field was nearly destroyed and only produced about one-fifth the yield of the field following standard guidelines.[94] Studies conducted in numerous other states also found that in most seasons early-sown wheat suffered moderate to heavy damage, whereas wheat sown later escaped fly infestation. As an example, a study conducted at eight locations over eight years in Illinois showed that on average wheat sown after the fly-safe date yielded 29 percent more than wheat sown before the date.[95]

More recent studies by modern agronomists show similar results. As an example, in 1981 when researchers took no precautions on test plots near Colfax, Washington, the entire crop was destroyed.[96] To gain perspective, we asked three senior agronomists who specialized in wheat culture what would have happened, given the conditions prevailing in the early twentieth century, if farmers had not followed the normal precautions. Their collective response was "those farmers would not have had a wheat crop worth harvesting."[97]

fly are almost surely lower bound, because when farmers adjusted varieties and cultural practices to avoid the fly there were real costs in terms of yield losses and increased exposure to winterkill and rust. The USDA estimated in 1904 that annual wheat losses to all insects were "at least 20 percent of the crop." Marlatt, "Annual Losses," p. 468.

[91] Hyslop, *Losses Occasioned by Insects*, p. 9.

[92] As an example, see Fletcher, *Pennsylvania Agriculture*, pp. 147–48.

[93] Headlee and Parker, "Hessian Fly," p. 115.

[94] McColloch, "Hessian Fly," pp. 91–94.

[95] Metcalf and Flint, *Destructive and Useful Insects*, pp. 410–11.

[96] Cook and Veseth, *Wheat Health*, p. 56.

[97] Interviews with Charles Schaller, interview by authors, Davis, California, 27 February 2001; Robert Webster, interview by authors, Davis, California, 25 April 2000; and Calvin Qualset, interview by authors, Davis, California, 25 April 2000. The fly would not have been a serious problem in every year, but the level of destruction in most years probably would have been higher, and severe outbreaks would have been more frequent and more widespread. Recent research shows the Hessian fly remains

These findings lend credence to the 1909 assessment of C. L. Marlatt, a leading scientist with the U.S. Bureau of Entomology, that the "prevention of loss from the Hessian fly, due to knowledge of proper seasons for planting wheat, and other direct and cultural methods, results in the saving of from $100,000,000 to $200,000,000 annually."[98] Relative to Marlatt's reference value for the wheat crop ($500 million), the biological investments to control this one pest led to yield savings of 20 to 40 percent. It is important to note that the Hessian fly was only one of a large number of insects, including grasshoppers, chinch bugs, and greenbugs that posed more severe threats as grain culture expanded.[99]

The Red Queen had yet another arrow in her quiver, because during the period under investigation there was a serious deterioration in the weed environment in part due to new introductions from other parts of the world. Referring to the northern Great Plains, Salmon asserts, "weeds were not an important factor on the new lands until near the end of the century," and for California he notes that "previous to 1900 any improvements in per acre yield resulting from a choice of better varieties and from the increasing use of fallow probably were more than offset by the increase in weeds."[100] Along with bindweed and wild oats, among the most damaging was Russian thistle, a tumbleweed, which entered the United States in the mid-1870s. The "best authorities" place and date the thistle's introduction to Scotland, South Dakota, around 1873. The weed spread to Iowa, Nebraska, and North Dakota by 1888, to Minnesota, Wisconsin, Illinois, and Indiana by 1890/91, and Kansas, Montana, and Idaho by 1894. Adapting to the times, the thistle hitchhiked rides on the railroad, reaching as far east as New York and as far west as California by the mid-1890s. Where it became established, the weed caused crop losses estimated between 15 and 20 percent. An Illinois observer noted: "No other weed has caused such widespread discussion, or been the subject of such great fear." In the 1890s numerous states and the USDA initiated successful programs to destroy the weeds. We have a natural experiment that suggests what might have happened without control measures. In Russia, with no similar collective efforts, "the cultivation of crops has been abandoned over large areas. . . ."[101] In spite of widespread anti-weed campaigns, USDA experts estimated that, by the early twentieth century,

the "number one" wheat pest. It is important to understand that the farmers still need to change varieties to combat the Hessian fly because the insect continues to mutate to "find a way around the plants' defenses." See Talley, "Hessian fly genomics."

[98] Marlatt's estimates recognize that even with preventative measures the Hessian fly caused losses in the order of about 10 percent of the annual wheat crop in early in the twentieth century. Marlatt, "Losses Due to Insects," p. 308. Identical estimates appear in Marlatt, "Annual Losses," p. 463 and in Dondlinger, *Book of Wheat*, p. 174.

[99] Olmstead and Rhode, "Biological Innovation."

[100] Salmon et al., "Half Century," pp. 16 and 19.

[101] Clinton, *Russian Thistle*, pp. 87–97; and Dondlinger, *Book of Wheat*, pp. 151–52.

weeds reduced the yield of spring wheat by 12–15 percent and of winter wheat by 5–8 percent.[102]

Our discussion has only touched on a few of the most important of the hundreds of insects, diseases, and weeds in the Red Queen's arsenal in her war on wheat. But there is a common pattern. In all cases the severity of the potential problems grew significantly between 1839 and the early twentieth century, and in all cases the actions of scientists, government agencies, and individual farmers in changing cultural practices dramatically reduced the severity of the problems.

RETHINKING PARKER–KLEIN'S ESTIMATES OF THE SOURCES OF PRODUCTIVITY GROWTH

In light of the settlement and Red Queen effects, it is important to rethink Parker–Klein's estimates of the sources of nineteenth-century labor-productivity growth for wheat. We shun the heroic task of modeling how diseases and pests might have evolved differently and how the wheat economy might have changed if biological technologies had stagnated. Rather we simply impose our estimates of the importance of integrated pest management systems and new varieties on top of the Parker–Klein analysis. Our counterfactual asks what would land and labor productivity have been in wheat cultivation in 1909 if grain growers continued using 1839 varieties and failed to invest to combat the rising threats from insects, weeds, and plant diseases. This exercise assumes the 1909 distribution of wheat acreage. We next estimate how much of this 1909 acreage would have fallen below a plausible yield threshold of commercial viability.

Table 6 details our estimates of what 1909 yields and output per hour of work would have been in the absence of the biological changes. This exercise is in the spirit of modern "crop loss assessment" in the agricultural sub-discipline of plant protection. Even today, one of the leading practitioners notes "crop loss assessment is not an exact science . . . the alternative would be no estimates at all."[103] This is precisely what the existing literature has done by implicitly attributing zero weights to the investments made to ward off yield declines. Our approach is intended to produce conservative, lower-bound estimates of the impact of biological investments. In line with the experience during the 1950s when durum yields fell by over 70 percent due to the emergence of stem rust race 15B, the literature suggests that in the absence of biological adjustments to control damage, disease epidemics and pest problems would have soon gotten out-of-hand, inflicting staggering yield losses.

To capture the direct effects of varietal changes, we use Parker and Klein's 1839 yields in their Northeast, South, and West: Corn Belt regions in place of the 1909 yields. For the other regions of the West, we follow the

[102] Cates, "Weed Problem," p. 205.
[103] Oerke, "Estimated Crop Losses," p. 72.

TABLE 6

THE ESTIMATED IMPACT OF BIOLOGICAL INNOVATION ON LAND AND LABOR PRODUCTIVITY IN 1909

						R3 Breakdown				
	Period	United States	R1 Northeast	R2 South	R3 West	Corn Belt	Western Dairy	Small Grain and Western Cotton	Range	California and Northwest
Yields										
1: Actual	1	11.3	14.5	8.4	13.0	13.0		ND	ND	ND
2: Actual	2	14.0	17.5	12.3	14.0	15.8	15.3	12	18.6	19.4
3: Counterfactual	2	7.5	13.1	7.6	7.3	10.4	6.5	5.6	9.3	10.0
4: Relative to actual		0.54	0.75	0.61	0.52	0.66	0.42	0.47	0.50	0.51
Yield adjustments										
5: Varieties			1839 Yd	1839 Yd		1839 Yd	2/3*1909 Yd	2/3*1909 Yd	2/3*1909 Yd	2/3*1909 Yd
6: Insects and weeds			0.90	0.90		0.80	0.80	0.80	0.80	0.80
7: Plant diseases			1.00	1.00		1.00	0.79	0.87	0.93	0.96
Total labor per bushel										
8: Actual	1	3.167	3.082	3.563	2.838	2.838		ND	ND	ND
9: Actual	2	0.759	1.024	1.404	0.690	0.762	0.760	0.690	0.952	0.433
10: Counterfactual	2	1.246	1.309	2.102	1.132	1.041	1.570	1.262	1.682	0.686
Bushels per hour										
11: Actual	1	0.316	0.324	0.281	0.352	0.352		ND	ND	ND
12: Actual	2	1.318	0.976	0.712	1.449	1.312	1.316	1.449	1.051	2.309
13: Counterfactual	2	0.803	0.764	0.476	0.883	0.960	0.637	0.792	0.595	1.458

Notes: The regions R1, R2, R3 (and its subregions) refer to Parker and Klein's regions. See the text of footnote 11 for regional definitions. In 1839 the Corn Belt and Western Dairy are not segregated. The yield adjustments are based on assuming (a) the Northeast, South, and West: Corn Belt regions used 1839 varieties and received 1839 yields; (b) following Salmon that yields in other regions of the West are two-thirds of 1909 yields; (c) insect and weed losses are 10 percent everywhere and an additional 10 percent higher in the West region first hit by the Hessian fly, the chinch bug, and other insects after 1839; (d) the plant disease losses in the new areas of the West equal the difference between the average and the peak three years in the 1919–1939 period as indicated in the *Plant Disease Reporter* and *Plant Disease Bulletin*.

lead of Salmon et al., and reduce the 1909 yields by one-third. The relatively poor performance of China Tea and Lost Nation vis-à-vis Fife in the North Dakota-Minnesota trials, as well as the subsequent widespread switch from Fife to yet higher yielding hard red spring and durum varieties by 1909, suggest that our assumed 33 percent decline in yields would be an under-estimate for the northern grain belt. The same conclusion applies to the Pacific region, which between 1839 and 1909 witnessed important changes in the location of production, several wholesale turnovers in varieties, and the development of cultural methods different than those found in the East.

To account for the adjustment for the increasing insect and weed problems, we reduce yields by 10 percent everywhere and by an additional 10 percent (for a total of 20 percent) in the West, which first suffered serious infestations of Hessian flies, chinch bugs, and other insects after 1839. The 20-percent figure is likely a serious under-estimate of the pest control savings because it is equal to Marlatt's 1909 lower-bound estimates of the saving from Hessian-fly-prevention measures alone, and thus ignores the vigorous efforts directed against locust, chinch bugs, green bugs, tumble weeds, and hundreds of lesser animal and plant enemies of wheat.[104]

An equally important task is to quantify the effect of controls for plant diseases. We can construct lower-bound regional estimates of the magnitude of the difference between potential and actual losses by examining the excess damage reported during periods of serious disease outbreaks. Our estimates use the state-level loss estimates published in the *Plant Disease Bulletin* and *Plant Disease Reporter* over the 1919–1939 period to compare damage in the worst three years with the average damage. This results in yield losses averaging about 11.5 percent nationally.[105] We take this estimate to represent the additional decline in yields due to diseases if biological technologies had remained constant.

There is a risk of double counting—the same wheat crop cannot be killed by the Hessian fly and then be damaged again by other insects or rust. (On the other hand, a crop weakened by one enemy might be more susceptible to another.) To address this problem, we have taken lower-bound loss estimates and adopted the standard practice in the crop-protection literature of modeling the percentage losses as having a compound or multiplicative effect rather than an additive effect on yields.

The resulting upper-bound counterfactual yield estimates, presented in Table 6 (Row 3), generate a stark picture. Without biological innovations, 1909 yields in Parker and Klein's West region (R3) would have been about

[104] As noted previously, Marlett's lower-bound estimate is well below the fly losses noted in most case studies in which recommended procedures were not followed.

[105] *Plant Disease Bulletin,* 1917–1922; and *Plant Disease Reporter,* 1923–1939. This is a lower-bound estimate because in the complete absence of biological learning, diseases likely would have evolved to be far more devastating than they were during the "bad" years of the relatively enlightened 1919–1939 period. By region, the excess losses were West: Dairy, 21 percent; Small Grain, 13 percent; Range, 7 percent; and California and the Northwest, 4 percent.

one-half of what was actually achieved. They would have fallen to roughly 7.3 bushels per acre, attaining low, noneconomic levels in many sub-regions of the West. In other regions, yields would have been about one-third lower than actually achieved. National yields would have been about 54 percent of those actually achieved in 1909 and about 67 percent of those prevailing in 1839.[106]

Inserting the revised yield estimates into the Parker and Klein framework offers a fresh perspective on the sources of growth in labor productivity. Parker and Klein show that nationally bushels per hour of labor increased from 0.316 in 1839 to 1.318 in 1909 (Rows 12 and 13), meaning labor productivity increased by 4.17 times. But our estimates show that without biological innovation, bushels per hour of labor in 1909 would have increased to only 0.803. By this reckoning, biological innovations increased the output per hour of labor by 0.515 bushels (that is, subject to rounding, 1.318–0.803) accounting for about one-half of the total increase in labor productivity.

Using our alternative yield estimates, U.S. wheat production circa 1909 would have been 46 percent lower. This calculation presumes that all land planted to wheat in 1909 remained in wheat. This is unlikely. With lower yields, substantial acreage would have dropped below the threshold for sustained commercial viability in grain production. Although commercial viability clearly depends on input and output prices, a breakpoint of 6.5 bushels per acre can serve as a rough-and-ready standard. Yields below this breakpoint were commonly considered "poor crops" or "failures" and very little wheat, less than 1 percent of 1909 output, was produced in counties with average yields less than this level.[107] Applying our yield adjustments to the county-level wheat-cultivation data from the 1909 census offers an estimate on how much acreage would not have been viable. These calculations show that without biological learning over one-quarter (28 percent) of U.S. wheat land in 1909 would have fallen below our 6.5 bushel standard. Much of this acreage would presumably have remained rangeland. Of course, the reduction in production might have increased prices, leading to shifts back into wheat cultivation in the East.[108] The key point remains that without biological learning the story of American agriculture over the nineteenth and early twentieth centuries would have been fundamentally different.

[106] These changes are consistent with the analysis of Salmon et al. for the first half of the twentieth century. This invaluable study found that the improved varieties introduced since 1900 increased annual output by about 231.8 million bushels or roughly 21 percent of 1949 output. Salmon et al., "Half Century," p. 110.

[107] See, for example, Patton, *Relationship of Weather*, p. 43.

[108] Removing the unviable acreage from the cropland base would have reduced 1909 wheat production by an additional 10 percent. It would also increase "measured" land and labor productivity relative to that reported in the counterfactual estimates.

CONCLUSION

In the mid-nineteenth century John Klippart, the corresponding secretary of the Ohio State Board of Agriculture, was arguably the most informed individual in the United States on wheat culture. In 1860 he published a 700-page tome detailing much of what was then known about the wheat plant and wheat farming.[109] In his view the commercial wheat belt would be forever limited to Ohio, Pennsylvania, and western New York. The soils and climate of Illinois, Iowa, and Wisconsin would doom those states to the haphazard production of low-quality and low-yielding spring wheat. Further west the climate and soils made any wheat production unlikely. The entire territory south of southern Indiana and southern Illinois could never yield reliable crops because of rust. As a result, unless the United States husbanded its resources it would soon be an importer of wheat.

How could Klippart have been so off the mark? He obviously was familiar with the mechanical reaper and thresher, and he would not have been surprised by the next generation of harvesting equipment—the self-binder. These are the machines that the standard accounts assert made the settlement of the West possible. What so colored Klippart's vision was his inability to foretell the wholesale changes in the genetic make-up of the wheat varieties that would become available to North American farmers. Mechanical inventions certainly lowered the cost of growing wheat in the West, but the binding constraint was biological. Without a biological revolution (assisted by the transportation revolution), the centers of wheat production in the United States and Canada could not have assumed their late-nineteenth-century dimensions.[110] In addition, during the nineteenth century the disease, pest, and weed environments seriously deteriorated. If generations of wheat farmers had simply followed in their fathers' footsteps (apart from adopting labor-saving machinery), their crops would have been ravaged.[111]

Nineteenth-century biological innovations were also important because they provided the foundation for the Green Revolution; much of the genetic material that modern wheat breeders used to produce the first generations of post–World War II hybrids came from Turkey wheat and other late-

[109] Klippart, *Wheat*; also see Ohio State Board of Agriculture, *Annual Report for1857*, pp. 675–816.

[110] A reading of the histories of Australia and Canada lends support to our emphasis on the importance of biological change in the nineteenth and early twentieth centuries. If the logic underlying the traditional view for the United States were sound, one might reasonably expect to find a similar emphasis on mechanization in the histories of other land abundant and labor scarce frontier economies. This is not the case. The Canadian literature emphasizes the crucial role that new rapid fruiting and drought- and cold-tolerant varieties played in western settlement, and in particular credits Charles Saunders's path-breaking achievement in creating Marquis. In a similar fashion, the Australian literature emphasizes the critical importance of drought-hardy and rust-resistant varieties developed by William Farrar. Mechanization plays a prominent role in the histories of both nations, but there is a clear recognition that biological innovation was essential for the expansion of the wheat belts in both countries.

[111] This is still true today because in recent decades about 40 percent of all wheat research was needed just to maintain yields. Adusei and Norton, "Magnitude of Agricultural Maintenance Research," pp. 1–6.

nineteenth- and early-twentieth-century introductions from around the world. In 1969, 11 varieties of hard red winter wheat were grown on one million or more acres. Turkey was important in the pedigree for all of these varieties. More generally, our findings suggest that the high rate of return to agricultural research is not just a modern phenomenon beginning with the spread of hybrid corn.[111] Mark Alfred Carleton's introductions of foreign wheat varieties and Charles Saunders's creation of Marquis are beacons of wise government investments. Cyrus McCormick has long been eulogized as the man who "made bread cheap." But he needed considerable help. It is time that we add the names of Mark Alfred Carleton, William and Charles Saunders, and David Fife to the high pantheon of nineteenth-century inventors for their role in revolutionizing North American wheat production.

[111] In their meta-analysis of the literature on rates of return to agricultural R&D, Alston, Marra, Pardey, and Wyatt reported an overall mean across 1,128 observations of 65 percent per annum. As well as the average, they discussed the large range of reported rates of return, and a general tendency for the rates of return to be biased up as a result of commonly used estimation methods. Alston and Pardey suggest that these biases notwithstanding, agricultural research has nevertheless been a highly profitable investment. Alston et al., "Research Returns Redux," pp. 185–216; and Alston and Pardey, "Attribution."

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