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BIOLOGICAL INNOVATION AND AMERICAN AGRICULTURAL DEVELOPMENT

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Alan L. Olmstead

The Green Revolution of the post-World War II era represents one of the most dramatic episodes in the history of agriculture. But, as we marvel at the recent accomplishments, it is important to remember that the world experienced two other Green Revolutions. Roughly 5,000 years ago the Neolithic Revolution gave the participants and their descendents unbelievable advantages over all who had lived before. The domestication of wheat, pigs, and horses, along with the invention of the wheel rank among the major achievements of the ages. Whereas the details of the Neolithic Revolution are shrouded in the darkness of a distant past, we can at least symbolically date the advent of the next great revolutionary epic.

The Second Green Revolution began on October 12, 1492, when Columbus set foot in the West Indies. This unleashed an extraordinary story of worldwide biological change and productivity growth in agriculture that is still playing out five centuries later. In the wink of an eye, Columbus pushed the world's agricultural production possibility frontier off the page.[1] All of the wondrous agricultural achievements of the most recent Green Revolution would be hard-pressed to match the significance of the introduction of maize outside the Americas, let alone the combination of maize with potatoes, sweet potatoes, tomatoes, cassava, peanuts, cocoa, tobacco, rubber and the dozen other crops of New World origin. The flow of biological technologies also went in the other direction—from the Old World to the New World.

The discoveries of the Americas and Australia raised the potential land endowment per European sixfold![2] The newly conquered lands acted as a magnet attracting Europeans and their plants and animals. The colonization began slowly and grew to a crescendo between 1840 and the outbreak of World War I when over 50 million people crossed the oceans.[3] In the process, the better part of three continents, comprising roughly 40 percent of the earth's useable land, was wrestled from the control of indigenous peoples. As the frontiers pushed outward, settlers repeatedly attempted to introduce both Old World and New World crops and animals into a succession of regions about which

[1] The effects were not all positive. The indigenous peoples of the "discovered" lands—be they the Indians of North and South America, the Maoris of New Zealand, the Aborigines of Australia, or the countless others inhabiting smaller areas—all met the horrible fate of people suddenly exposed to diseases for which they had no immunities. In many cases the native peoples ceased to exist; in all cases they endured a holocaust that saw their numbers shrink to a small fraction of the pre-contact age. Alfred W. Crosby, *Ecological Imperialism: The Biological Expansion of Europe, 900-1900* (Cambridge: Cambridge University Press, 1986).

[2] Kevin H. O'Rourke, "The European Grain Invasion, 1870-1913," *The Journal of Economic History* Vol. 57, No. 4 (December 1997), p. 775 (775-801).

the newcomers had little practical information. This was intrinsically a biological process as farmers and governments gradually unlocked the mysteries of local soil characteristics (or at least their capabilities), climate, and cultural practices required for agricultural success. The economic transformation of three continents was a huge undertaking that ranks among the great achievements of all time.

For the most part we think that technologies are not location specific—for example a pump invented in the United States will work equally well in Canada or Mexico.[4] To some extent this is true for agricultural technologies—but there are serious constraints. A key lesson of history is that agricultural production processes are location specific, dependent on conditions that may differ from one farm to the next and certainly differ in the next state or region. This is particularly true of biological inputs as opposed to mechanical factors. Crop varieties and a host of cultural decisions must be harmonized with very specific local soil and climatic conditions. Given this imperative, one might reasonably speculate that biological learning would have significantly increased land productivity in an age when the adaptation of agriculture onto untried lands was a dominant feature of the development of the United States (as well as Canada, Argentina, Australia, and New Zealand).[5] Although this seems a reasonable view, it is at odds with the received wisdom of the preponderance of the economics and agricultural economics literature dealing with the agricultural development of the United States. This literature focuses on the relative factor scarcities in the United States and argues that rational farmers should have adopted labor-saving machinery. This seemingly reasonable insight has led scholars to focus on the diffusion of labor-saving mechanical innovations (of which there were many), and to all but ignore spectacular land-augmenting innovations.

In his Richard T. Ely Lecture, D. Gale Johnson succinctly captures this general view. "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 and followed over the next several decades with equally major improvements in the yields of grain sorghum, wheat, rice, and cotton."[6] More generally, Johnson has maintained that land-augmenting investments were relatively unimportant until the World War II era. Hayami and Ruttan's work repeatedly echoes this important theme. As an example, when dealing with the history of small grains in 19th century US, they note that "the advances in mechanical technology were not accompanied by parallel advances in biological technology. Nor were the advances in labor productivity accompanied by comparable advances in land productivity."[7] As another example Willard Cochrane notes that mechanization "was the principal, almost the exclusive, form of farm technological advance" between 1820 and 1920.[8]

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[3] Crosby, p. 300.

[4] This insight offers one major reason underlying the "catch up hypothesis;" late bloomers can relatively cheaply acquire the store of knowledge and technologies developed and paid for by the economic leaders.

[5] Indigenous peoples had long practiced agriculture on these lands. But the new settlers had no prior experience; and, for the most part, both the crops and the cultural technologies that they introduced were novel to the areas.

[6] D. Gale Johnson, "Agriculture and the Wealth of Nations," *American Economic Review*, 87:2 (May 1997), pp. 7-8.

[7] Yujiro Hayami and Vernon Ruttan, *Agricultural Development: An International Perspective*, revised and expanded edition, (Baltimore: The Johns Hopkins University Press, 1985), p. 209.

[8] Willard W.Cochrane, *The Development of American Agriculture: A Historical Analysis* (Minneapolis: University of Minnesota Press, 1979), p. 200, also see p. 107.

The notion that the 19th century was largely an era of labor-saving productivity change in agriculture is also a part of the official mantra of most economic historians. The estimates allocating efficiency changes in American grain farming between land- and labor-saving technologies, that are the starting point for most discussions, come from William Parker and Judith Klein's 1966 study. They found, that between 1840 and 1910, the output per unit of labor increased by about three-and-one-half times, while the output per unit of land only increased by about 10 percent. They attributed the vast majority of the increase in efficiency to mechanization.[9]

There are two powerful reasons for accepting this general position. First, it appears consistent with the data—in the United States, average yields per acre harvested of most crops increased little, if at all, over that broad span of the 19th and early-20th centuries. Secondly, there are conceptual reasons for embracing this view of the stylized facts because it conforms nicely to the predictions of the induced innovation model. To quote again from Hayami and Ruttan: "…the evolution of the mechanical equipment is designed to bring about larger output per worker by increasing the land area that can be operated per worker. Furthermore, it seems apparent that the production functions which described the individual grain-harvesting technologies, from the sickle to the combine, were induced by changes in relative factor costs, reflecting the rising resource scarcity of labor relative to other inputs."[10]

Let us deal first with the latter, conceptual issue. As Paul Rhode and I have shown elsewhere, the stylized facts of America's past, as known by most agricultural economists, were not in conformity with either the actual data or with the more specialized agricultural history literature.[11] The differences are significant and need to be accounted for in our conceptual modeling. In particular, the actual changes in relative factor scarcities over the past one-and-one-half centuries generally ran precisely counter to what has been claimed in the induced innovation rendition of American history. Most importantly, the long run relative price of land was moving in the wrong direction to explain mechanization in the century before 1910. Rather than labor becoming dearer relative to land, it was land that was becoming more expensive. As an example, crude estimates suggest that the weeks of agricultural labor required to purchase an acre of farmland more than doubled between 1790 and 1850 and then approximately tripled between 1850 and 1880. Furthermore, from the perspective of the induced innovation model, the post-1920 biological revolution simply could not have happened at a worse time, because this was the only extended period in the past 120 years when relative fertilizer prices were rising instead of falling. The upshot of these findings is that we have no conceptual reason whatsoever for believing that farmers and innovators should have had a desire to save labor relative to other factors—if anything the movement in factor prices should have led farmers to augment land, all else equal. Thus, we should be freed from whatever constraints the induced innovation model might have placed on our ordering of the past.

The induced innovation model emphasizes the role of demand in determining the pace and pattern of innovation, but there are also supply side forces that need to be considered. It is often argued that biological and chemical breakthroughs were somehow more difficult than the developments underlying mechanization and that the

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[9] William N. Parker and Judith L. V. Klein, "Productivity Growth in Grain Production in the United States: 1840-60 and 1900-10," in *Output, Employment and Productivity in the United States after 1800*, National Bureau of Economic Research: Studies in Income and Wealth, Vol. 30, 1966.
[10] Hayami and Ruttan, p. 79.
[11] Olmstead and Rhode, "Induced Innovation In American Agriculture: A Reconsideration," *Journal of Political Economy* Vol. 101, No. 11 (1993), pp. 100-118.

former had to await fundamental advances in basic science before they could proceed.[12] This view is at the same time right and wrong. Yes, the modern genetic revolution and the development of hybrids in fact required sophisticated advances in basic science. But the fixation on the biological revolution in the United States supposedly starting with the development of hybrid corn, has led us astray. Throughout the literature dealing with other countries, the term "biological change" often refers to a more general category of land-augmenting investments that are contrasted with labor-saving mechanical changes. Thus, given the terminology common to the literature, "biological changes" include the application of fertilizers, building irrigation or drainage systems, double cropping or otherwise increasing the intensity of land use, the introduction of new plant varieties or breeds of animals, the use of chemicals to control diseases and pests, improved cultural practices, and the host of other innovations that might enhance land productivity. Such innovations generally did not require the same level of sophistication, as did the breakthroughs in hybridization.

Examining the evidence on land-augmenting productivity changes will be the primary task of the remainder of this paper, but let me start by acknowledging what I have already said. The US data show that yields per acre for most crops were relatively constant until roughly the 1940s when they shot up. The post-World War II period has been a revolutionary period of land-augmenting productivity changes. But does this mean that the general view, classifying the period before 1940 as primarily an era of mechanical (labor-saving) change, and the period after 1940 as primarily an era of biological (land-saving) change, is accurate? Absolutely not! Between 1910 and 1940, crude indicators of output per unit of land in the United States grew at a rate of about .94 percent per year. Over the next 40 years, between 1940 and 1980, output per unit of land grew at 1.95 percent a year, or more than double the previous rate. But, a look at the change in the growth of labor productivity shows a striking result. Between 1910 and 1940 labor productivity in agriculture grew at 1.4 percent per year; but between 1940 and 1980 it grew at 5.5 percent per annum or over three-and-one-half times as fast. Both land and labor productivity growth rates soared in the post-World War II era, but to dub this period the era of biological change and the former period the era of mechanical change is clearly misleading.

With this background, let me summarize where we stand and provide the bare outline of my case. The existing literature's fixation on mechanical changes (in part, generated by the seductive appeal of the induced innovation model) has led wise and knowledgeable scholars to downplay or ignore the significance of land-augmenting investments in the development of US agriculture. The simple Hicksian model, suggesting that a rise in the relative price of one factor of production should lead to technological change to save that factor, has much appeal.[13] However, advocates of this view of the world have a serious problem because, between roughly 1800 and 1940, the changes in relative factor prices moved exactly counter to what much of the literature assumed. The popular vision of cheap agricultural land on the frontier is accurate but needs to be supplemented. First, to obtain useful quantities of land was generally expensive because the land had to be cleared of trees, drained, and fenced—as I will show,

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[12] Cochrane, pp. 201-202.

[13] But, in addition to developing substitutes for their scarce resources, farmers also should seek to develop complements for their abundant resources. Thus, the introduction of a new wheat variety that allows for the expansion of the wheat frontier complements the abundant "raw" land. The key insight is that there are some biological changes that are substitutes for land such as fertilizers and fertilizer intensive crops. But another class of biological changes, such as hard winter and spring wheat varieties, complemented land. In the context of 19th century America, this latter class of innovations makes sense within the induced innovation framework.

over the 19th century these types of investments dwarfed the investments in mechanization. In addition, there was often a critical learning curve that had to be surmounted in order to convert newly settled lands from open range to cropland. It generally required decades, and sometimes the better part of a century, to gain the knowledge and biological technologies (such as new grain varieties) needed for success. Once permanent agriculture was established, crops and animals were invariably confronted with devastating attacks of pests and diseases. Many of these attackers simply migrated from established agricultural areas within the US, but a significant number were new arrivals that were an inevitable consequence of the vast and largely uncontrolled international trade in plants and animals. To understand the impact of non-mechanical innovations on increasing agricultural productivity requires that we look beyond the usual display of data showing yields per acre and ask what would have happened without investments in the maintenance of yields. Once we look, it becomes apparent that, by changing varieties and cultural practices, 19th and early-20th century farmers had considerable success in limiting the damage caused by pests and diseases. Ignoring these kinds of maintenance investments has led the literature to miss many of the productivity-enhancing innovations of the era.

As I tell my story, I suspect that most of you are apt to find yourselves thinking, "I knew that." Moreover, I fully expect that even the scholars that I am criticizing will agree with me. They should, because I have drawn many of the insights and examples that I am about to present from the works of Hayami, Ruttan, Johnson, Cochrane, Parker, etc. On many occasions economists have stubbed their toes on biological and other land-augmenting innovations without grasping their overall significance. Let me start where my case is strongest and briefly recount the well-known story of the trials and tribulations of California's, and to a significant extent the world's, grape producers in the 19th century.

THE GRAPE AND WINE INDUSTRIES

The second half of the 19th century witnessed a significant expansion of grape growing in California. This is a fascinating story of biological learning as thousands of entrepreneurs spent fortunes trying to match vines with favorable local geoclimatic conditions. It took well over half a century of continuous effort to discover that the coastal valleys of Northern California produced wine grapes superior to those of other regions of the state. Some of the mistakes were gargantuan, as when Leland Stanford (ex-governor, railroad magnate, and university benefactor) built one of the world's largest vineyards and wineries in the Red Bluff area (north of Sacramento) where the summer temperatures regularly soar above 110 degrees Fahrenheit.

The most famous of the pioneers of the California wine industry was the flamboyant Hungarian immigrant Agoston Haraszthy, a self-styled Count, Colonel, and "Father of California Wine." His story encompasses many of the lessons of the development of viticulture in California and shows the importance of biological learning in the ultimate success of the state's agriculture. Haraszthy's first stop was in Wisconsin, where he made a considerable investment in planting vines and constructing a large wine cellar. Predictably, he failed. Next, he settled in San Diego in 1850 and planted vineyards that came to nothing. His third try was in San Francisco where he planted vines as part of a larger nursery project. The cold, foggy, weather doomed that effort. This was followed by a venture in the mountains of San Mateo County just south of San Francisco where he planted 30 acres of vines in 1854. Once again, he failed due to the cold, damp, climate. After considerable research he purchased 560 acres in Sonoma County in 1856 where at last, on his fifth attempt, he occupied land suitable for growing table wines. Haraszthy was no fool—far from it; we can speculate that he thought carefully before investing his capital and efforts into each of his failed ventures. The fact that he was so far off the mark simply indicates how ignorant farmers were about the biological and climatic factors needed for success, and the importance of trial and error experiments to determine what would work. Even those growers who, based on their experiences in Europe, had an inkling about what the vines required, often had little appreciation of the local soil fertility and climatic conditions. Such an appreciation required surveys, soil analysis, and years, if not decades, of recording rainfall, temperature, etc.[14]

On his Sonoma land, Haraszthy built the Buena Vista Winery, one of California's landmark establishments. By the end of 1857 he had planted 26,000 vines and by 1859 his workers were tending roughly 280 varieties, many of which Haraszthy had imported from Europe. But what sets Haraszthy apart (aside from his penchant for self-promotion) was his tour of Europe in the summer and fall of 1861. At a time when real officers were lining up to fight for their country, "Colonel" Haraszthy, armed not with a rifle but with a commission from the California state government and a letter of introduction from the US Secretary of State, set out on a fact finding voyage to garner information on European vines and wines. His trip carried him through the prime winemaking areas of France, Germany, Italy, and Spain. In all, Haraszthy and his agents shipped about 100,000 vines (with roughly 300 varieties) to his California estate (many were from areas that he did not himself visit such as Hungary, Morocco, Anatolya, and the Crimea). Although many of the varieties that Haraszthy collected undoubtedly already existed in California, his trip nonetheless stands out as a major scientific feat that contributed to the growth of the California wine industry. [15]

In the history of the California grape industry, we see a pattern that was repeated for most crops and in most new areas of settlement—long bouts of experimentation and widespread failure that were coupled with a worldwide search for new and improved plant varieties. The reason to start our parade through America's agricultural past with grapes is because of the catastrophes that befell this industry, and the example that this industry offers regarding the importance of investments to maintain yields. The battles against the pests and diseases that threatened grapevines represent an important story in the history of 19th century agriculture. The Voyages of Discovery led to an unprecedented trade in biological technology, but the exchange of flora across the oceans had enormous biological costs as well as benefits. The early settlers of North America repeatedly attempted to plant European vines (vinifera) on the eastern seaboard. From the 16th to well into the 19th centuries literally thousands of individual efforts to transplant European grapes failed because the vines soon fell victim to plant diseases endemic in North America, but unknown in Europe. Two of the most destructive were powdery mildew and phylloxera.[16]

Powdery mildew (also known as *oidium*) is a fungus that grows on the leaves, stems, and fruit and is easily transmitted over wide areas by windblown and water-born spores. Infected plants wither; the grapes crack and remain acidic. By the 1840s, powdery mildew was attacking vines across France and by the early 1850s it had

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[14] Paul Rhode, "Learning, Capital Accumulation, and the Transformation of California Agriculture," *The Journal of Economic History* 55:4 (December 1995), pp. 773-800.

[15] John N. Hutchison, "Northern California from Haraszthy to the Beginnings of Prohibition," in Doris Muscatine, et al., eds. *Book of California Wine* (Berkeley: University of California Press, 1984), pp. 30-37; Pinney, pp. 275-77; Carosso, pp. 38-48.

spread throughout much of southern Europe and into Asia Minor and North Africa. The results were devastating with losses often ranging between 50 and 90 percent of the crop. Hardest hit was the island of Madeira, where most of the population depended on the vines for their livelihood. The arrival of powdery mildew in Madeira in the 1850s destroyed the economy, causing great hardship and mass emigration.[17]

The vines of Europe were saved by science. A. M. Grison, a botanist/gardener at the Palace of Versailles, began experimenting with chemical remedies in the late-1840s and rapidly discovered that plants sprayed with a lime-sulfur compound remained healthy. This soon lead to the more economical method of dusting the vines with sulfur. By the early-1860s most French vines were regularly being treated—they still are. The knowledge of how to control powdery mildew was widely publicized in California by the late-1850s and, perhaps for this reason, there is little mention of the disease in the Golden State.[18] Europe's experience with mildew was but a prelude to an even more devastating American invasion—phylloxera.

Phylloxera is a louse that sucks the vines' roots; the plants lose vigor and usually die within three or four years. Phylloxera was endemic in the eastern United States and was carried to Europe sometime before 1863 and to California about a decade later as part of a vast trade in plants.[19] By the mid-1870s, the disease was ravaging the prime growing areas of northern California. According to Carosso, more than 400,000 vines were dug up in Sonoma County alone between 1873 and 1879. The disease spread unabated through the 1880s, and by the early-1890s most of the vineyards of Napa Valley were infected.[20]

As with the case of powdery mildew, advances in biological knowledge eventually gave growers the upper hand in the battle against phylloxera, but the costs were staggering. Experiments conducted in both France and the United States during the 1870s and 1880s investigated hundreds of possible chemical, biological and cultural cures; most, including the application of ice, toad venom, and tobacco juice proved ineffective. Four treatments appeared to offer some hope: submerging the vines for periods of about two months under water, the use of insecticides (namely carbon disulfide and potassium thiocarbonate), planting in very sandy soils, and restocking the vines by grafting onto resistant, native-American, rootstocks.[21] Only replanting on resistant rootstocks proved economically feasible, and even this course of action required an extraordinary investment. In an age when the economics literature focuses almost exclusively on mechanical innovations, the vast majority of the vines in the world were methodically torn out so that the vineyards could be replanted with European varieties grafted onto American roots. This was a slow and painful process that resulted in severe hardship in the grape producing areas of the world. The

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[16] Other dreaded vine diseases included black rot and downy mildew. Lucie T. Morton, *Winegrowing in Eastern America* (Ithaca, NY: Cornell University Press, 1985), pp. 27-31; in California the grape leafhopper and red spiders also attacked the vines. Butterfield, p. 31.

[17] George Ordish, *The Great Wine Blight* (London: Sidwick & Jackson, 1987 ed.), pp. 14-18; Pinney, p. 25.

[18] Pinney, pp. 24, 171; Ordish, pp. 1-19. Carosso does note that in 1879 late frosts and mildew significantly reduced yields in California. Carosso, pp. 46, 49, 99.

[19] Carosso dates the arrival in Europe between 1858 and 1863, p. 110. According to Pinney, "The disease had been discovered as early as 1873 in California" (p. 343), but this was when it was first positively identified by the Viticultural Club of Sonoma. Carosso maintained that the "disease was known to have existed in California before 1870…,"and vines on the Buena Vista estate probably had shown signs of infestation as early as 1860. See Carosso, pp. 109-11; Butterfield, p. 32.

[20] Carosso, pp. 111, 118.

[21] Ordish, pp. 64-102. Ordish and most others use arcane 19th century terminology, labeling "carbon disulfide" (CS_2) as "carbon bisulfide" or "carbon bisulphide," and "potassium thiocarbonate" K_2CS_3 as "sulphocarbonates of potassium."

battle against phylloxera also represents an incredible biological feat; today most of the world's 15 million plus acres of vineyards are the product of the scientific advances and investments made in the 19th century. A few details of this story will offer a better sense of the achievement.

A number of early American growers had hit on the idea of grafting foreign vines onto American roots. But grafting had no effect on black rot and the various mildews that typically killed vinifera well before the phylloxera could do its damage. This, along with the generally unfavorable climate in the eastern states meant that grafting was not widely pursued. In the United States, the idea of grafting onto American rootstocks to resist phylloxera reemerged in the 1860s and 1870s with the pioneering works of Charles V. Riley in Illinois and Missouri, Eugene Hilgard in California, and George Husmann in Missouri and California.[22]

Once the general principle of replanting on American rootstocks was established, much tedious work remained to be done and many detours and blind alleys had to be explored. Scientists and farmers had to discover which American varieties were resistant to phylloxera, which combinations of American and European varieties would graft well together, and which varieties of rootstock would flourish in a given region with its particular combinations of soil and climate. In addition, grafting techniques to improve success rates and cut labor costs had to be perfected. Solutions to these problems required considerable trial and error as well as formal scientific investigations.[23] In California, scientists working for the University of California, the Board of State Viticultural Commissioners, and the US Department of Agriculture all conducted experiments on a wide variety of vines and conditions. Similar efforts took place across Europe. As a result of the initiatives of Riley, Husmann, and others in Missouri, that state's nurseries became the leading producers of resistant rootstock for farmers across Europe. By 1880, "millions upon millions" of cuttings had already been shipped to France. Ordish estimates that France, Spain, and Italy would have required about 35 billion cuttings to replant their vineyards (most of these would have been grown in European farms and nurseries after the first generations were supplied from America). To better appreciate the physical magnitude of this undertaking, 35 billion cuttings would have required roughly 12 million miles of cane wood—enough to circumnavigate the earth about 500 times![24]

It would be desireable to have a quantitative assessment of the social savings or the rate of return to biological investment in preventing the worldwide destruction of the grape, raisin, and wine industries; I will leave that task to someone else. To give a sense of the magnitude of the outcome of such an exercise, France today would be a nation of beer drinkers or perhaps vodka swiggers. Forty million Frenchmen would have to have been right about something else besides the wisdom of drinking wine.

The story of biological innovation, of which we have just scratched the surface, has long been a central theme in the history of 19th century viticulture. But, more generally, this story offers an example of the extent of the biological exchange between Europe and the Americas and of the role that scientific research played in enhancing agricultural productivity. The intensity and significance of biological efforts in the grape and wine industries is

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[22] Morton, pp. 30-31; Ordish, pp. 21, 103; Carosso, pp. 113-27; Pinney, pp. 392-95.

[23] As an example, the first US varieties shipped to France were labrusca and labrusca-riparia hybrids that had a low resistance to phylloxera. In California the initial recommendation that growers in California use vitis californica for rootstock proved to be a mistake. Pinney, pp. 345, 394; Carosso, p. 125; Ordish, pp. 116-119**.**

[24] Pinney, pp. 345, 392-95; Carosso, pp. 125-26; Ordish, pp. 114-115. To my knowledge, only Chile escaped having to replant its vines; Ezequel Martinez Estrade once lamented that "Chile was the worst located country on this planet." In this instance Chile's remoteness undoubtedly was an advantage.

widely appreciated in part because there were relatively few mechanical changes to complicate the story. In addition, most of us can appreciate the distinction between a good and a bad wine—between a fine Cabernet and rotgut. Thus, changes that promote higher quality are fairly apparent. But does the experience of California's grape industry reflect a broader pattern, or is it an outlier?

BIOLOGICAL INNOVATION AND THE TRANSFORMATION OF CALIFORNIA AGRICULTURE

In fact, the experience of California's grape growers was strikingly similar to that of most of the growers of specialty crops for which the state is now known. There is a general pattern. The Franciscan Padres first introduced most of the state's fruit and nut crops in the 18th century. For the most part, these were relatively low quality selections compared to what came later—thus the mission grape compared with the scores of more refined varieties, the mission black fig compared with the white fig of Smyrna, etc. Over the course of the next 150 years, farmers experimented with new varieties, grafting techniques, different soils, and varying cultural practices. This was a gradual process with two steps forward invariably followed by at least one step backward. The many failures led to hundreds of thousands of trees being uprooted and destroyed.[25] As the best niches for a given crop were discovered and exploited, large concentrations of one or perhaps a few crops emerged. As examples, prune production centered in the southern areas of Santa Clara county (near San Francisco), oranges and lemons in the Greater Los Angeles area (San Fernando, Riverside, Valencia), pears in the Sacramento River basin, raisin grapes near Fresno, high quality wine grapes in the Napa, Sonoma, and Central Coast counties, and so on. Professional nurseries emerged to hasten the diffusion of new and improved varieties.

When California gained statehood in 1850, the area was relatively free of pests and plant diseases. Rampant and uncontrolled importation of biological materials changed all that, and by about 1870 a succession of invaders attacked the state's crops, threatening the commercial survival of many horticultural commodities. In addition to grape phylloxera, some of the major pests that were introduced or became economically significant between 1870 and 1890 "were San Jose scale, woolly apple aphid, codling moth, cottony cushion scale, red scale, pear slug, citrus mealybug, purple scale, corn earworm, and hessian fly." Among the diseases to emerge in the 1880s and 1890s were "pear and apple scab, apricot shot hole, peach blight, and peach and prune rust."[26] Large orchards of single varieties added to the problem by creating an exceptionally receptive environment for the pests, and the state's nurseries further contributed to the difficulties by incubating and spreading diseased plants. Thus, within a few decades, California's farmers went from working in an almost pristine environment to facing an appalling list of enemies in an age when few effective methods had been developed anywhere for cost efficient, large-scale pest control. Here again there was a general pattern. At first the losses were often catastrophic. This led to tearing out and burning orchards, to quarantines, to the development of chemical controls, to a worldwide search for parasites to

[25] As an example, the sandy soils of the lower San Joaquin Valley proved unsuitable for peaches because of the pests and diseases that these soils harbored; as a result over 2 million trees were removed between 1920 and 1940. Warren P. Tufts, et al., "The Rich Pattern of Crops," in Claude B. Hutchison, ed., *California Agriculture* (Berkeley: University of California Press, 1946), p. 194.

[26] Ralph E. Smith, et al., "Protecting Plants From Their Enemies," in Claude B. Hutchison, ed., *California Agriculture* (Berkeley: University of California Press, 1946), p. 245.

attack the new killers, and to efforts to limit losses by developing new cultural methods and improved varieties that were resistant to the pests or diseases. University of California and government scientists spearheaded these various efforts and together made numerous stunning breakthroughs that fundamentally altered the course of California agriculture. With this general outline, let me offer some historical detail to buttress my case.

San Jose scale and the codling moth first appeared in California in the early 1870s with disastrous results throughout the state's deciduous fruit orchards by the early 1880s. These threats were among the proximate causes underlying the creation of the State Board of Horticultural Commissioners in 1883 and the passage of the state's first horticultural pest-control and quarantine law. The introduction of arsenic-based sprays, such as Paris Green, gave farmers the ability to control the codling moth.[27] Other chemical formulas, including petroleum-based sprays, lime-sulfur mixtures, lye solutions, and Bordeaux Mixture (a copper-lime compound) all entered the fray. The latter product, developed in France by Millardet, proved to be one of the most important advances ever in the history of agricultural chemistry and was used extensively to combat mildews and fungi. University of California scientists also conducted detailed trials to determine proper dosages, the best times for application, and preferred droplet sizes for a long list of chemicals, thereby improving their worth in the field. These same scientists also took the lead in gaining important legislation to certify the properties of agricultural chemicals and thus helped drive adulterated and ineffective products from the market. In the same period, research conducted on both sides of the Atlantic unlocked many of the mysteries regarding fungal diseases leading to effective controls by spraying. In addition, major breakthroughs in fumigation technology and in the development of modern spraying and dusting equipment date to the last quarter of the 19th century—many taking place in California.

The attempt to control insects with other insects represents one of the most fascinating stories of biological success in the pre-1940 era. California scientists, often in collaboration with colleagues in Australia, scoured the globe to find parasites that would devour harmful insects; the results were often spectacular. As an example, cottony cushion scale first appeared in California's citrus groves during the industry's infancy in the early-1870s (it was probably introduced from Australia). By the 1880s, the damage was so extensive that the entire industry appeared doomed. Attempts to control the scale with all manner of sprays were largely ineffective and scientists turned to experimenting with fumigating the orchards. Aware that cottony cushion scale existed, but did little damage in Australia, American scientists turned their attention to discovering why. In 1887 the USDA sent Albert Koebele, an entomological collector, to Australia in search of predators. Koebele hit the jackpot, sending back ladybird beetle colonies (vedalia or *Rodolia cardinalis*) to a colleague in Los Angeles. Within a year after general release, the voracious beetle had reduced cottony cushion scale to an insignificant troublemaker, thereby contributing to a three-fold increase in orange shipments from Los Angeles County in a single year. According to one historian of this episode, "the costs were measured in thousands and the benefits of the project were undetermined millions of dollars."[28]

This success encouraged Koebele to make another journey to Australia where he discovered three more valuable parasites helpful in combating the common mealybug and black scale. Other entomologists made repeated insect safaris to Australia, New Zealand, China, and Japan, as well as across Africa and Latin America. There were

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[27]Smith, et al., pp. 248, 257.

[28]Smith, et al., pp. 249-250; Lawrence A. Graebner, "An Economic History of the Fillmore Citrus Protective District," Ph.D Dissertation, Department of Economics, University of California, Riverside, 1982, pp. 30-34.

many failures, but by 1940 a number of new introductions were devouring black scale, yellow scale, red scale, the Mediterranean fig scale, the brown apricot scale, the citrophilus mealybug, the long-tailed mealybug, and the alfalfa weevil. In addition, scientific investigations led to improved ways of breeding various parasites so that they could be applied in large numbers during crucial periods.[29] As with Koebele's initial successes, the rate of return on these biological ventures must have been astronomical.

To this point, my discussion has only scratched the surface of the biological technologies that diffused in the pre-World War II era. Applied biological and chemical developments similar to those described above had a significant impact on the production of a wide spectrum of field, truck, and horticultural crops. Furthermore, the wholesale transformation from land-extensive crops that required relatively little labor per acre to high-value labor-using crops and the vast expansion of the state's irrigation and flood control systems represented massive land-augmenting investments. These changes rivaled the significance of strictly labor-saving mechanical technologies in California. This is a controversial statement because among those mechanical technologies was the combine harvester, which was first commercially produced and used in California. The key point is that land productivity increased due to the intensification that accompanied the changing of crop mixes which itself required an enormous amount of biological investment. Thus, looking at the relative importance of "mechanical" versus "biological" technological changes for any one crop in a given region completely misses the impact of the general pattern of land intensification. As we shall see, this is also an issue of great significance for other states.

COTTON

Was California an exception, or were biological changes in other regions and for other crops also far more important than the economics literature would have us believe? In particular, what about the key staple crops? A close reading of Hayami and Ruttan should alert us that something might be amiss.
On page 209 they note that "the advances in mechanical technology were not accompanied by parallel advances in biological technology." But in a footnote they note: "This is not to imply that significant advances in biological technology were not achieved; for example, 'all of the farmers of the Lower South accepted as their standard strain a new upland cotton developed by Southwestern plant breeders during the early decades of the 1800's. The new variety, the famous Mexican hybrid, improved the yield and quality of American cotton to such an extent that it deserves to rank alongside Eli Whitney's cotton gin in the Old South's hall of fame.'" [30]

Given that cotton is one of the great staples of American agriculture, and given that the cotton gin holds an exalted place next to the reaper, combine, and tractor on the high altar in the grand temple of labor saving inventions, this is a startling claim that deserves more attention. Circa 1790, high quality Sea Island cotton had just recently been introduced and was prospering in selected regions on the Atlantic seaboard. Elsewhere, various short staple upland cottons were being grown. By 1800, a new and improved upland variety, Tennessee Green Seed, had been developed in the Cumberland Valley, and was gaining favor elsewhere.[31] This variety represented a considerable

[29] Smith, et al., pp. 250-555.
[30] Hayami and Ruttan, p. 209.
[31] James L. Watkins, *King Cotton* (New York: Negro Universities Press, 1908, reprinted in 1969), pp. 100 and 254.

improvement because it could be picked about 20 to 25 percent faster than the previous upland varieties. In Mississippi, the dominant variety was Creole Black Seed. A bacterial disease introduced around 1811 spread rapidly through Mississippi and neighboring areas, causing devastating loses. In response, growers in the Lower South increased their plantings of Tennessee (or Georgia) Green Seed that was initially resistant to rot, but offered lower quality.[32] But within a few years, Green Seed also succumbed to rot.

The first of a long chain of events that would transform southern cotton production occurred in 1806 when a Natchez area planter, Walter Burling, obtained seeds of a high quality cotton in Mexico City, which he promptly proceeded to smuggle out of Mexico. Burling passed the seeds on to a fellow planter and local scientist, William Dunbar, who began the tedious process of experimenting and increasing the seed.[33] Dunbar also sent samples of fiber to Liverpool to be tested for spinning quality. By the 1810s the Mexican cotton was prospering in the Natchez area where it was mingled with the local varieties. The hybrid that emerged was a vast improvement:

> Its staple was longer and the grade of the lint higher than Creole or Green Seed. It ripened earlier in the fall than any other type then in cultivation in the United States, and it displayed a noticeable tendency to mature many of its bolls simultaneously. Even more importantly, it possessed exceptional picking properties. Its large four or five-sectioned bolls opened so widely upon ripening that their lint could be plucked from the pod more easily than any other known variety of the staple. Because of this unusual quality, pickers could gather three to four times as much Mexican in a day as they could the common Georgia green seed cotton. Most important of all, the Mexican strain was totally immune to the rot, the dreaded plant disease that was then destroying both the Creole and Georgia Green Seed crops in Mississippi.[34]

The Mexican variety rapidly spread throughout the South in the 1810s and 1820s.[35]

Over the antebellum years, there was an enhanced understanding of breeding techniques that led to further successes.[36] By the early-1830s, the efforts of Mississippi breeders yielded an even superior variety, Petit Gulf, which also was easy to pick and rot resistant. A problem was that the mixing of seeds at gins tended to reduce the average quality unless the grower selected the seed with care. This led to the growth of specialized seed producers in Mississippi who shipped throughout the South.[37] The evolution in cotton breeds was primarily responsible for the

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[32] John Hebron Moore, *The Emergence of the Cotton Kingdom in the Old Southwest, Mississippi, 1770-1860* (Baton Rouge: Louisiana State University Press, 1988), pp. 12-13; John Hebron Moore, *Agriculture in Ante-Bellum Mississippi* (New York: Bookman Associates, 1958), pp. 13-36.

[33]Dunbar was also experimenting with other varieties, including one from China. John Hebron Moore, "Cotton Breeding in the Old South," *Agricultural History* 30:3 (July 1956), p. 96. By 1800, southern planters had experimented with cottons from Cypress, Smyrna, China, Brazil and the West Indies. Even Sea Island Cotton which became the basis for the early industry probably did not arrive in North America until the mid-to-late-1780s. Lewis C. Gray, *History of Agriculture in the Southern United States to 1860,* vol. II (New York: Peter Smith, 1941), 673-677. Burling was on an official mission to Mexico and smuggled the cotton seeds out of the country hidden in a number of dolls. The unauthorized transfer of "intellectual property" was a major ingredient in the development of American agriculture. Gilbeart H. Collins, *The Production of Cotton* (Boston: Stanbope Press, 1926), p. 201; Watkins, *King Cotton*, p. 165. Moore, 1958, pp. 32-33.

[34]Moore, 1956, p.97; also see Gray, pp. 689-90; John Hebron Moore, *Agriculture in Ante-Bellum Mississippi* (New York: Bookman Associates, 1958), pp. 13-36.

[35] Watkins, *King Cotton*, p. 13.

[36] John Hebron Moore, "Cotton Breeding in the Old South," *Agricultural History* 30:3 (July, 1956), quote from p. 97; pp. 95-104; John Hebron Moore, *The Emergence of the Cotton Kingdom in the Old Southwest, Mississippi, 1770-1860* (Baton Rouge: Louisiana State University Press, 1988), pp. 12-16.

[37] Moore, 1988, p.13.

increase in daily picking averages from about 50 pounds per worker in 1800 to roughly 200 pounds in 1860.[38] In addition, the improvements in cotton varieties led to significant increases in the yields per acre.[39]

There were many other examples of improvements in varieties in the pre-World War II era which had substantial impacts. As examples, the USDA developed the long-staple Pima in the first decades of the 20th century from seeds imported from Egypt. Alcala cotton was "discovered" in 1906 by USDA scientists who were scouring Guatemala and southern Mexico in of search varieties that might be resistant to the boll weevil. Acala seeds were carried to Texas that year and numerous experiments and selections ensued to adapt strains for specific areas. In 1920 the USDA introduced Acala to California where it became the only variety planted on any scale for over 40 years.[40] More generally, in the early-1920s the Arkansas Experiment Station listed 442 varieties of cotton in the United States.[41] Recall that at the end of the colonial period only a few varieties were known to have existed. This offers a graphic illustration of the attention devoted to biological innovation.

In addition, there were a host of cultural changes that required years to perfect. Important innovations in the time of planting, the density of seeding, and in plowing practices affected land productivity. Early in the 19th century, southern farmers generally plowed up and down hillsides, thus unnecessarily creating horrible erosion problems. Enlightened farmers such as William Dunbar experimented with the development of horizontal plowing techniques and campaigned to convince his reluctant neighbors to adopt his new system. Horizontal systems (with gentle slopes and drainage ditches) continued to be perfected and adopted over the pre Civil War era, with vast savings to the landscape.[42] The fall in fertilizer prices and the growth of a commercial fertilizer industry following the Civil War noticeably expanded the feasible area of cotton production.[43] Biological learning was also crucial in limiting the damage from pests. The boll weevil entered Texas in the 1890s and by 1920 had reached the eastern seaboard. Local communities were often devastated by the infestation. Everywhere, growers adapted by significantly changing cultural practices, opting for earlier planting, earlier ripening and more resistant varieties,

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[38] No reliable studies summarize picking yields over a large number of farms with varying conditions, and no studies decompose the sources of yield increases. The above estimates of increases from 50 to 200 pounds per worker reflect a consensus from the sources already cited and from Stanley Lebergott, *The Americans* (New York: W. W. Norton & Company, 1984), pp. 168, 176. The change in location of production along with changes in labor organization and supervision could have accounted for some of the increase in picking rates. But contemporaries give the bulk of the credit to improved varieties. It is significant to note that between 1860 and the diffusion of the mechanical cotton picker almost a century later, there were only modest increases in picking efficiency.

[39] Between 1800 and 1840, a period when annual southern cotton production increased from 40 to 871 million pounds, Whartenby estimates that yields per acre increased by 46 to 78 percent. But these estimates do not consider the counterfactual that without the infusion of new varieties, yields would have declined significantly due to diseases. Franklee Gilbert Whartenby, pp. 54, 104-105. Many other factors in addition to a change in varieties were at play because the center of cotton production moved onto more fertile western lands, but production was also moving from high yielding valleys to upland regions.

[40] Gilbeart H. Collins, *The Production of Cotton* (Boston: Stanbope Press, 1926), p. 206-213; John Turner, *White Gold Comes to California* (Bakersfield, California: California Planting Cotton Seed Distributors, 1981), pp. 40-41. The dominance of Alcala in California was more a function of government policy than of the variety's superiority. John H. Constantine, Julian M. Alston and Vincent H. Smith, "Economic Impacts of the California-One Variety Cotton Law," *Journal of Political Economy* 102 (October 1994), pp. 951-74.

[41] Gilbeart H. Collins, *The Production of Cotton* (Boston: Stanbope Press, 1926), pp. 236-247.

[42] Gray, p. 689-70; John Hebron Moore, *The Emergence of the cotton Kingdom in the Old Southwest, Mississippi, 1770-1860* (Baton Rouge: Louisiana State University Press, 1988), pp. 30-34.

[43] Wright, p. 111; Rosser Taylor, "Fertilizers and Farming in the Southeast, 1840-1950," *North Carolina Historical Review* 30 (1953), pp. 314, 327.

more fertilizer, the application of calcium arsenate, and giving much more attention to cleaning their fields after the harvest to reduce the weevil's habitat.[44]

As noted above Hayami and Ruttan thought that the story of cotton was an exception and thus relegated it to a footnote. But far from an exception the cotton experience reflects a general pattern common to most crops. We saw this pattern already in the discussion of the introduction of new crops and new varieties into California. The crucial insight is simple and straightforward—there is no sleight of hand. The economics literature is correct that national output per acre of a given crop was relatively constant, but the area of production along with the soil and weather conditions kept changing. It was the intensification of agriculture in these new regions, for example the movement from open range to cotton production, that represented a key source of 19th century productivity growth. The history of cotton at least partially validates my introductory speculation. In an age when the settlement of three continents was the key feature of agricultural development, how could biological learning not be a dominant ingredient in the growth of agricultural productivity. The history of wheat further reinforces this view.

WHEAT

Once again, if one ignores the general conclusions, the economics literature provides strong hints that biological changes might have been important sources of productivity growth in the pre-World War II wheat economy. As an example Hayami and Ruttan note that "the entire significance of this sequence of innovations in grain harvesting was to increase labor productivity. To the extent that any impact on land productivity was involved, it was a factor contributing to the expansion of grain production into the drier areas of the Great Plains, where grain yields were lower than in the eastern grain-producing regions."[45] One would do well to ask what other factors besides machines contributed to the extension of wheat farming onto the Great Plains. Johnson and Gustafson's imaginative and path breaking analysis of the sources of productivity growth in US grain production in the post-World War I era still sets the standard for the profession, but it only offers a hint of the potential longer-run effects of biological change. In an effort to determine the importance of varietal changes in the period between 1928 and 1954 they regressed average yield per seeded acre and average yield per harvested acre on nine independent variables including an index of newness of varieties seeded. They decomposed the United States into Eastern and Western states because the United States as a whole is too heterogeneous an area with respect to wheat production to be treated in a single analysis. Using the regression estimates, they constructed estimates of the net effect of varietal newness on the regional average yields. For the Western region they found that between 1928 and 1954 wheat yields increased by 2.45 bushels from 11.7 to 14.15. Of this increase approximately 60 percent was due to the introduction of new varieties. Although informative, Johnson and Gustafson's methodology does not allow us to fully address the impact of new varieties. This is because the formal analysis does not take a long enough perspective, and it does not capture the substantial decreases in yields that might have occurred due to the onset of rust and other diseases and pests if varieties had remained static. This is clear from their discussion of the difficulties that farmers growing

[44] Gavin Wright, *Old South, New South*, p. 122; Douglass Helms, "Technological Methods for Boll Weevil Control," *Agricultural History* 53 (1979), 286-99; Douglass Helms, "Revision and Revolution: Changing Cultural Control Practices for the Cotton Boll Weevil," *Agricultural History* 54 (1980), 108-25; Kent Osband, The Boll Weevil Versus King Cotton," *Journal of Economic History* 45 (1985), 627-43.

durum wheat experienced in these years. As Johnson and Gustafson state: "Our analysis of varietal changes in wheat seems to imply that much of the research on new varieties constitutes to a considerable extent a maintenance operation. The fact that improved small grain varieties have not had the effect of increasing yields by as much as experimental comparative varietal tests does not mean that the research efforts have not been valuable and should not be continued or even expanded. In the absence of the research and the adoption of new varieties it is quite clear that the yields of the small grains would have declined over time."[46] Johnson and Gustafson proceed to offer an example as to how important such "maintenance operations" might be:

> The heavy attacks of black stem rust on durum wheat in 1952, 1953, and 1954 indicate the very considerable necessity of continually developing new varieties. The average yield of durum wheat per seeded acre for the decade 1942-51 was 14.5 bushels; in 1952 the yield was 9.7; in 1953, 6.2; and in 1954, 3.0. During the same three years other spring wheat yields were roughly comparable to the long-time average. By 1956 rust resistant varieties were available on a significant scale and yield had returned to normal levels. In 1958 a record yield of 23.8 bushels per acre harvested was achieved despite the fact that climatic conditions were such that rust losses would have been heavy had it not been for the rust-resistant varieties.[47]

One method of combating diseases has been to shift to more resistant varieties. In this context, Johnson and Gustafson note that "for the US as a whole, the USDA quinquennial wheat variety surveys indicate that, on average during the survey years 1944, 1949, and 1954, around 40% or more of US wheat acreage was seeded with varieties not grown, or grown in only limited amounts, five years previously."[48]

Here, our task is to determine if similar shifts were occurring in an earlier age and what their impact was on the spread of wheat culture into the arid west and on the control of diseases and pests. Given the extent of the data, it is difficult to be as precise as one might like, but nevertheless the evidence suggests that biological change was crucially important on both counts. For the most part, the galaxy of evils that might befall a wheat crop in 1860 would have been familiar to farmers in the 1940s. Continued cultivation of wheat in a region invited infestations of the Hessian fly, the midge, and the chinch bug. Stem rust, blight, and smut also caused serious damage, and in many areas, winter kill was always a threat. The conventional wisdom asserts that the Hessian fly and the midge were relatively late arrivals to the United States. The fly reportedly arrived in 1776 in the straw of Hessian mercenaries, and the midge worked its way into New England from Canada in the 1820s. It spread rapidly and by 1830 was reported in New York. Both had a devastating impact, leading in many cases to the abandonment of wheat, particularly in hard hit areas of New York.[49]

Well before the American Civil War scientists and farmers, through a process of careful observation, developed an understanding of the life cycle of the major pests.[50] In addition, there is clear evidence that farmers

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[45] Hayami and Ruttan, p.79.
[46] D. Gale Johnson and Robert L. Gustafson, *Grain Yields and the American Food Supply* (Chicago: University of Chicago Press, 1962), p.120.
[47] Johnson and Gustafson, p. 120.
[48] Johnson and Gustafson, p. 119.
[49] *The Agricultural Census of 1860*, pp. xxxi-xlv.
[50] In some cases farmers also made headway in understanding diseases. In New England and in parts of Europe, farmers observed that wheat growing in proximity of barberry bushes was more apt to be damaged by stem rust. In 1660 farmers in Rouen, France took steps to tear out the bushes. In 1726 Connecticut passed a law empowering town meetings to eradicate the bushes and Massachusetts and Rhode Island enacted similar legislation in the mid-

were changing varieties and cultural practices on a regular basis in an attempt to ward off some of the harmful effects of insects and plant diseases. Farmers learned that they could reduce the damage caused by the Hessian fly by sowing late in the fall after the first frost (or for spring wheat, early in the season), and by better cleaning their fields. As an example of the extent of these cultural changes, one local account from Connecticut indicates that by 1811 the date of planting had shifted from the third week in August to the end of September or early October.[51] Efforts to combat the fly also led to the search for and adoption of new wheat varieties. The most important was a bearded red winter wheat (called Mediterranean) that was introduced from Europe in 1819.[52] Farmers also learned that early harvesting could defeat the most serious effect of the midge. This discovery led to further changes in cultural practices such as draining soggy lands and planting on drier fields so that the harvest could be moved up. But most importantly, it further increased the value and adoption of Mediterranean wheat which, by the standards of the time, both ripened early and could be sown late. By the 1850s, Mediterranean wheat had become the dominant variety in the United States, primarily because of its pest resistant qualities, even though its flour quality and yield were inferior to many varieties.[53]

The search for even better varieties was in full gear. Danhof notes that around 1840 a survey listed 41 varieties being grown in New York state, "of which, nine winter wheats and nine spring wheats were most important."[54] Nearly two decades later, in 1857, the Ohio State Board of Agriculture offered an analysis of the wheat varieties grown or recently grown in the state. The report offered impressions on the time of ripening, performance in different types of soils and in different regions of the state, and flour quality. It also commented on resistance to rust, the Hessian fly, and the midge. The report listed 111 varieties, 96 winter wheats and 15 spring wheats. Of these, it was possible to identify when 86 first entered Ohio. Twenty-four, or 28 percent, of these varieties had been introduced within the past 5 years.[55] In 1866 the newly formed Department of Agriculture conducted field experiments with 55 varieties of winter wheat and 67 varieties of spring wheat. The tests included

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18th century. In 1865 De Bary scientifically demonstrated the role of barberry bushes as a host for stem rust. Yet, this knowledge was slow to diffuse. Hamilton suggests that the widespread presence of barberry bushes may have contributed to stem rush epidemic that devastated the Minnesota wheat crop in 1878. It was not until 1918 that Minnesota outlawed the barberry bush. At this time the USDA initiated a campaign to eradicate barberry bushes in 13 North Central states. Between 1918 and 1939 over 22 million bushes had been destroyed. Carleton R. Ball, "The History of American Wheat Improvement," *Agricultural History* 4:2 (1930), pp.48-71; Laura M. Hamilton, *Minnesota History* 20:2 (June 1939), pp. 156-164; E. C. Lange, *The Advance of Fungi* (New York: Henry Holt, 1940), pp.121-146; Robert B. Elwood, et al., *Changes in Technology and Labor Requirements in Crop Production: Wheat and Oats*, Works Progress Administration, National Research Project, Report No. A-10 (Philadelphia: WPA, 1939), p. 80.

[51] Percy W. Bidwell and John I. Falconer, *History of Agriculture in the Northern United States, 1620-1860* (Washington, DC: The Carnegie Institute of Washington, 1925), p. 96.

[52] As is often the case there are conflicting stories as to this wheat's origin. Klose claims that it came from the Mediterranean islands, but the *Ohio Agricultural Report for 1857*, pp. 700-701, asserts that the variety came from Hesse via Holland.

[53] The often-repeated quote of "an excellent farmer" found in the Ohio Agricultural Report that "three-fourths, if not nine-tenths of the wheat raised in this country is the Mediterranean variety," appears to be an exaggeration. A review of the Patent Commissioner Reports for the late 1840s and the early 1850s suggests that Mediterranean was the most common variety, but Blue Stem, Zimmerman, White Flint (Soule's variety), and various types of Purple Straw were also frequently mentioned. US Patent Office, various years.

[54] Clarence H. Danhof, *Changes in Agriculture: The Northern United States, 1820-1870* (Cambridge, Massachusetts: Harvard University Press, 1969), p. 157.

[55] *Ohio Agricultural Report for 1857*, pp. 737-761. Given that there was often much confusion regarding wheat names it is likely that some varieties were listed under different names.

varieties from the Mediterranean, "nine from Glasgow, eight from the Royal Agricultural Exhibition at Vienna…, several varieties from Germany," and one from the Black Sea.[56]

Over the late-19th century the premier hard spring wheat cultivated in North America was Red Fife (which was identical to a variety known as Galician in Europe). As happens so often, a number of stories regarding its origin have gained currency; the following account is widely accepted. The grain was the descendent of a single wheat plant grown on the farm of David Fife in Otonabee, Ontario 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. (Hence, it was sometimes called Scotch Fife.) It was introduced into the US no later than 1860 when J. W. Clarke, a Wisconsin farmer and frequent correspondent for the *Country Gentleman*, recommended the hard red wheat.[57] Red Fife is recognized as the first true hard spring wheat and became the basis for the spread of the wheat frontier into northern Wisconsin, Minnesota and the Dakotas. It also provided much of the germ stock for later wheat advances, including Marquis.

Another notable change was the introduction of "Turkey" wheat, a hard red winter variety suited to Kansas, Colorado 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.[58] Malin's careful treatment suggests a long process of adaptation and experimentation, with the new varieties gaining widespread acceptance only in the 1890s. Wheat varieties from southeastern Europe proved relatively more successful in arid regions, leading the USDA to search for additional varieties.[59]

Also contributing to the spread of hard red wheat varieties after the American Civil War were improvements in flour milling technologies. Using the traditional stone-grinding methods, millers found hard red wheat yielded darker, less valuable flour than the softer white wheat varieties. (Indeed, this resulted in widespread complaints against semi-hard red varieties such as Mediterranean.) 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 hard red varieties. Over this period, flour from 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.[60] The introduction of new hard red varieties, combined with the innovation of processing technologies that increased their value to

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[56] *Report of the Commissioner of Agriculture for the Year* 1866 (Washington: GPO, 1867), p.8.

[57] David Fife was one of countless farmers attempting to develop improved varieties by selection. The common pattern was that farmers would discover that one plant somehow survived a rust epidemic or otherwise distinguished itself. The seed from this plant would then be carefully preserved and increased to build a new variety. The date of its entry into the United States is often given as 1860, but Clark, writing in 1860 noted that it had been grown extensively in the Northwest "for the last three seasons." *Country Gentleman*, Nov. 1 1860, XVI:18, pp. 282-83. The *Ohio Agricultural Report for 1857* also briefly mentions "Fife." p. 759.

[58] Carleton R. Ball, "The History of American Wheat Improvements," *Agricultural History*, p. 63. The Mennonites also brought Russian varieties of oats, barley and rye. In addition, they carried with them a wide assortment of garden, flower and fruit trees seeds. The seeds had been carefully selected kernel by kernel. The Turkey Hard Winter Wheat had only been introduced into southern Russia by the Mennonites 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. Harley J. Stucky, *A Century of Russian Mennonite History in America* (North Newton, KS: Mennonite Press, 1973), pp. 27-30.

[59] James C. Marlin, *Winter Wheat in the Golden Belt of Kansas* (Lawrence: University of Kansas Press, 1944).

[60] Henry A. Knopf, "Changes in Wheat Production in the United States," Ph. D Thesis, Cornell University, 1967, p. 233; James C. Malin, *Winter Wheat in the Golden Belt of Kansas* (Lawrence, KS: Univ. of Kansas Press, 1944).

consumers, allowed the spread of profitable grain cultivation to the Grain Plains. This represents an example of the synergism of biological and mechanical innovations.

As a rule breeders and farmers were looking for varieties that improved yields, were more rust resistant, and as the wheat belt pushed westward and northward, varieties that were more drought tolerant and more resistant to winter kill. Again the data are less than ideal, but the general progression in varieties allowed the wheat belt to migrate several hundred miles northward and significantly reduced the risks everywhere on the Plains. One of the most important of the early-20th century varieties was Marquis, which was bred in Canada by William Saunders who crossed Red Fife with Red Calcutta. Tony Ward's estimates of the decline in the ripening period at four Canadian experiment stations shows the remarkable impact of changing cultural methods and varieties. Between 1885 and 1910 the estimated ripening period on average fell by 12 days—days that meant the difference between success and failure in many years.[61] More generally, Kenneth Norrie's quantitative study of the settlement of the Canadian prairies between 1870 and 1911 found that pushing the wheat frontier further north and west required the adoption of dry farming technologies and the development of drought-resistant and early-ripening wheat varieties suitable for the region.[62]

Farmers' behavior offers an indication of the importance of the new choices in varieties. First, all indications suggest that over the 19th century farmers were regularly shifting to new varieties to combat yield-sapping diseases and pests and to find wheats that would perform in the colder and more arid west. These shifts may not have been as rapid as what took place in the mid-20th century. But this should not obscure the fact that over the century before 1940 these shifts fundamentally changed the character of the wheat varieties grown in North America, thereby playing a crucial role in facilitating the industry's expansion onto the Great Plains. In a nutshell, no hard red spring wheats are thought to have made their way into the United States before the mid-1850s and no hard winter wheats before 1873. In 1929, a decade before the onset of the biological revolution, over 80 percent of the wheat acreage planted in the United States consisted of varieties that did not exist in North America until 1873. Secondly, maps of the distribution of wheat varieties suggest that farmers were adopting varieties especially tailored for their particular soils and climate.[63]

We do not have a good measure of the counterfactual world depicting what would have happened to yields if varieties and cultural practices had stagnated—that is if biological technologies had remained constant over the 19th century. But Johnson and Gustafson's discussion of the catastrophic declines in durum wheat yields in the

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[61] Tony Ward, "The Origins of the Canadian Wheat Boom, 1880-1910," *Canadian Journal of Economics* 27:4 (November 1994), pp. 864-883. 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, pp. 175-76, credits Marquis with giving adopters about one extra week between harvest and freezeup, thus giving farmers a significant advantage in preparing their land for the next season.

[62] We attempted a rough test of importance of new hard winter and spring wheat varieties in the settlement of the western plains by looking at what happened to yields of "eastern varieties" in dry years. But we soon gave up, because during the worst droughts of the 19th century in the state of Ohio (where we had the best data), rainfall never dipped as low as the normal conditions in the western plains.

[63] J. Allen Clark, et al., "Distribution of the Classes and Varieties of Wheat in the United States," USDA Department Bulletin no. 1498, May, 1929; Mark A. Carleton, "Hard Wheat Winning Their Way," in *USDA Yearbook* (Washington: GPO, 1915), pp. 391-420; J. Allen Clark, et al., "Improvement in Wheat," in *Yearbook of Agriculture* (Washington: USDA, 1936), pp. 207-277.

1950s, along with numerous 19th century accounts of the problem of existing varieties "wearing out," offers a hint of the productivity-enhancing impact of varietal and cultural changes in an earlier age.[64]

PRODUCTIVITY CHANGES IN ANIMAL HUSBANDRY

The dairy industry represents an important part of our story because of its growing significance in the agricultural economy. By 1900 dairy production accounted for about 16 percent of all US farm output and by 1940 it accounted for about 30 percent. Writing near the turn of the past century, Henry Alvord, who was the Chief of the Dairy Division of the Bureau of Animal Industry, noted: "No branch of agriculture in the United States has made greater progress than dairying during the nineteenth century."[65] There was good reason for Alvord's enthusiasm. In the early part of the 19th century, dairying was at best a haphazard sideline for all but a few farmers. Milch cows belonged to the mongrel and indescribable race of "native" or "frontier" cattle. Pasture and feed was poor and the cows often went on starvation diets during the winter—providing food and shelter were labor and capital intensive activities and thus rationed. Cows typically calved in the spring and were allowed to go dry in the fall or early winter. Milk, butter, and cheese were produced in crude and unsanitary conditions and the quality was generally low. The growth of urban markets and improved transportation stimulated a gradual adoption of better practices. But the first cheese factory was not built until the early 1850s in New York state and the first creamery was not erected until a decade later. [66] This general situation changed dramatically over the next century.

Between 1850 and 1910 the national average milk yield per cow increased from 2,371 pounds to 3,570 pounds, or by about 51 percent. Even more surprising for the economists' stylized view of the 19th century is that over these same years, labor productivity actually declined nationally by about 20 percent and, in the important eastern and mid-western dairy regions, it declined by about one-third.[67] A look behind these numbers reveals an interesting regional pattern of development. In the New England and upper Middle Atlantic states, yields were already relatively high in 1850 (about 4500 pounds per cow) and increased by only about 7 percent by 1910. In other regions, yields began much lower and showed dramatic increases—300 to 600 percent in most southern and western states. In the important dairy states of Wisconsin and Illinois, yields rose by about 60 and 85 percent respectively. In addition, during this period there was a substantial compositional shift in production from high yield areas in the northeast to lower yield areas to the west and south. In 1850, 44 percent of the nation's dairy cows were in the northeast, but by 1910 that ratio had fallen to 25 percent.[68] This regional shift in production implies that without the effects of improving techniques and breeds, " the national average yield would have declined instead of

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[64] A look at the *Census of 1860* shows that large areas that had been prime wheat producing regions (especially in New York State) had been abandoned because of the problems with pests and diseases.

[65] Henry E. Alvord, "Dairy Development in the United States," in *Yearbook of the United States Department of Agriculture for 1899* (Washington: GPO, 1900), p. 381; also see, pp. 381-403.

[66] Alvord, pp. 381-86.

[67] Fred Bateman, "Labor Inputs and Productivity in American Dairy Agriculture, 1850-1910," *The Journal of Economic History* Vol. 29, No. 2 (June 1969), pp. 222-223.

[68] Fred Bateman, "Improvements in American Dairy Farming, 1850-1910: A Quantitative Analysis," *The Journal of Economic History* Vol. 28, No. 2 (June 1968), p. 263.

increasing."[69] Dairying is one case where, thanks to the contributions of Fred Bateman, it has long been recognized that yield increases stemmed from non-labor saving and non-mechanical innovations. "Before 1900, however, there were no mechanical improvements in dairying even remotely comparable to, for example, the mechanical reaper. Thus most of the influence on the diary production function and dairy efficiency had to originate from other (nonmechanical) sources, particularly improved breeds and feeding and care techniques."[70] Especially important was providing better feed and shelter over the winter months that allowed for a significant lengthening of the milking season.[71] Many of these developments had already occurred in the northeast, helping to explain the relatively low yield increases in that region. It is unlikely that the above output measures fully capture the actual changes that took place because of the limitations of the data and the difficulty in accounting for quality changes. In particular, as a result of increased cleanliness in milking and handling operations, milk and milk products became much safer to consume. In addition, the testing of cattle and the spread of pasteurization after the turn of the century all but eliminated tuberculosis in milk products in the US by 1940.

Two biological advances were of particular note in the later part of the 19th century. The introduction of ensilage allowed for better feeding over the winter and thus an extension of the milking season. This was a labor and capital intensive development. The first silo known to exist in the United States was built in Illinois in 1873, and it was about a decade later until a silo was built in Vermont.[72] By the mid-1920s, the state of Wisconsin alone had over 100,000 silos.[73] The other truly significant change was the Babcock butterfat test developed in 1890 at the University of Wisconsin. By improving the ability to monitor quality, this procedure reduced the free rider problem and gave farmers a strong incentive to adopt better practices and breeds.[74]

Data for the first half of the 19th century are scarce. An extensive descriptive literature suggests that in the northeastern states there had been a significant improvement in dairy breeds by 1860 relative to the type of cattle that existed at the end of the colonial period.[75] This impression is born out by inquiries made in 1800 by the Massachusetts Society for Promoting Agriculture suggesting that a "fair" amount for "ordinary cows" was about 2,500 pounds of milk per year.[76] Given that progressive farmers were more likely to participate in such surveys, this number probably overstates the actual situation by a good deal. In any case it would have significantly overstated the national average given the general backward nature of the southern dairy situation (in 1850, most southern states

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[69] Bateman, 1968, p. 264.
[70] Bateman, 1968, pp. 255-56.
[71] Bateman probably errs when he notes that mechanical changes had little effect because the adoption of the mechanical mower must have had an enormous impact on a farmer's ability to increase the hay supply over the winter months.
[72] Harold A. Meeks, *Time and Change in Vermont* (Chester, Connecticut: The Globe Pequot Press, 1986), p. 164.
[73] T. R. Pirtle, *History of the Dairy Industry* (Chicago: Mojonner Bros. Company, 1926), p. 64.
[74] Eric E. Lampard, *The Rise of the Dairy Industry in Wisconsin: A Study in Agricultural Change, 1820-1920* (Madison: The State Historical Society of Wisconsin, 1963), pp.153-62, and 197-204.
[75] Charles T. Leavitt, "Attempts to Improve Cattle Breeds in the United States, 1790-1860," *Agricultural History* VII:2 (April, 1933), pp. 51-67.
[76] This is reported in Percy W. Bidwell and John I. Falconer, *History of Agriculture in the Northern United States, 1620-1860* (Washington, DC: The Carnegie Institute of Washington, 1925), p. 229. The Society survey returns reported the reasonable ranges of butter and cheese produced by "ordinary cows." Pirtle converted these figures to roughly 2500 pounds of milk. Pirtle, p. 27.

averaged well below 1,000 pounds and none surpassed 2,000 pounds).[77] From these fragments of information, it is reasonable to assume that that national yield per cow at the end of the 18th century may have been as low as 1,000 pounds and most likely did not exceed 2,000 pounds. In 1940 milk yields were about 4,500 pounds, suggesting that yields probably increased from 2- to over 4-fold over the 140 years before the formal onset of the modern biological revolution—not a bad accomplishment for an age when biological change was supposedly inconsequential!

Bateman emphasized the importance of feeding and care of dairy animals over breed improvements in the period between 1850 and 1910. In fact, he had little solid information on the details of breed improvements, but we do know that there were considerable changes over the entire span of the 19th century. These changes began in the northeast and gradually diffused to other areas.[78] In 1800 there were almost no purebred dairy cows in the United States. By 1885 there were about 90,000 registered purebred dairy cattle in the US and by 1895 the number had grown to about 273,000. These animals had a significant impact on herd quality far beyond their actual number. According to Alvord, "their blood is so generally diffused that half-breeds or higher grades are very numerous wherever cows are kept for dairy purposes. Therefore, although pure-bred animals form less than 2 per cent of the working dairy herds, their influence is so great that it is probable the average dairy cow in the United States at the close of the century will carry nearly 50 per cent of improved blood. The breeding and quality of this average cow, and consequently her productiveness and profit, have thus been steadily advanced."[79] By the 1920s the evidence begins to come into sharper focus, with the number of dairy purebreds roughly tripling since 1900 to about 900,000 animals; by 1920 virtually all dairy cows were classified as grades.[80] As Table 1 indicates, none of these breeds were known to have existed in the United States at the beginning of the 19th century. Clearly, enormous improvements occurred after 1940. But these latter advances were built on the foundation established in the pre-World War II era during which time there were wholesale changes in the structure, managerial practices, knowledge, and the genetic base of dairying that significantly effected productivity.

The story of productivity changes in dairying parallels the broader trends in animal husbandry. As an example, the importation of shorthorns, along with better breeding practices and changing range conditions led to a change in the beef cattle population similar to what occurred with dairy cattle. Likewise, the importation of Merino sheep beginning early in the 19th century resulted in an increase in the average wool yield per animal by roughly 4-

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[77] Grey depicts the very backward status of dairy activities in the South during the Colonial period. Louis Cecil Gray, *History of Agriculture in the Southern United States to 1860*, vol. I (New York: Peter Smith, 1941), pp. 204-206.

[78] Percy W. Bidwell and John I. Falconer, *History of Agriculture in the Northern United States, 1620-1860* (Washington, DC: The Carnegie Institute of Washington, 1925), p. 132; Leavitt, pp. 51-67.

[79] Alvord, p. 392.

[80] Pirtle, pp. 35-56; C. W. Larson, et al., "The Dairy Industry," pp. 281-394 in *USDA Yearbook for 1922* (Washington: GPO, 1923), p.324-331; Houck, p. 187. Between 1900 and 1920 the percentage of purebreds among the dairy herds had roughly doubled from about 1.5 percent to about 3 percent, and the quality of the grade stock had also increased. Houck's numbers on the number of registered purebred dairy cattle are in rough conformity with the data offered above. Given that not all purebreds were registered, the actual numbers would be somewhat greater. Institutional structures, designed to provide the record keeping and certification necessary for increasing the quality of dairy cattle, also grew significantly. The American Ayrshire Breeders' Association dates to 1863, and by the mid 1880s similar organizations for the Holstein-Friesian, Jersey, Red Polled, and Guernsey breeds had been formed. The number of cow testing associations grew from 1 in 1906 to 777 in 1926, and the number of bull associations grew from 3 in 1908 to 225 in 1926. Pirtle, pp. 35-56.

fold between 1800 and 1940.[81] These and other cases of changes in animal husbandry all have interesting tales associated with the changes in demand, improvements in transportation, and evolving conditions on the range and in stockyards. But here I would like to concentrate on one important aspect of this larger story—the activities of the Bureau of Animal Industry and others in improving animal health and productivity.

The Bureau of Animal Industry was founded in1884 as a division within the USDA in response to growing concerns about the spread of contagious pleuropneumonia, hog cholera, and other diseases.[82] The Bureau's achievements represent one of the most neglected aspects of US agricultural development. By 1940 scientists in North America, Europe, and Australia (with Bureau scientists playing a major role) had unlocked the mysteries associated with a large number of diseases and taken major steps toward their eradication in the United States. A very partial list of these successes includes the campaigns against pleuropneumonia, Texas fever, foot and mouth disease, tuberculosis in cattle, the big head disease in horses, and hog cholera. In addition, the Bureau's agents made breakthroughs on scores of other relatively minor fronts such as discovering that removing roosters from laying flocks of chickens greatly reduced the deterioration of eggs during the summer months. [83] In the space here I shall concentrate on two cases—the campaigns against contagious pleuropneumonia and tuberculosis.

Beginning in 1884 the Bureau began an aggressive campaign to stamp out contagious pleuropneumonia. There had been precedent. The disease had entered Massachusetts via Holland in 1859 and rapidly infected cattle over a broad section of the state. On April 4, 1860 the state legislature passed an act that appointed three commissioners empowered to quarantine, kill and dispose of infected animals. When the first appropriation of $10,000 was exhausted, the Governor called a special session of the legislature to provide additional funding. Six years of vigorous efforts led to the eradication of the disease in Massachusetts in 1865. Connecticut had also repelled the disease on several occasions using similar methods.[84] But enforcement at the state level had obvious problems and by 1885 it was known to exist in seven states and the District of Columbia (outbreaks would subsequently appear in a number of other states). Through several acts of Congress, the Bureau's agents received authority and funding to quarantine large areas and to dispose of infected animals. Crucial to the success of this and subsequent campaigns was the initiation of a policy to compensate the owners of the diseased animals, thereby

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[81] The average wool yield was thought to have been about 1 to 2 pounds in 1800. By the Civil War era it had risen to about 4 pounds and by 1940 it was about 8 pounds. These estimates are especially crude because they include all sheep; a compositional shift in response to changing demand conditions away from meat producing breeds to wool producing breeds (or visa versa) would not imply an increase or decrease in productivity. Lebergott, p. 166; HSUS, Part I, pp. 517-20.

[82] Houck, pp. xi, 1-37. The BAI grew out of the Veterinary Division which had been established one year earlier.

[83] According to McMillen, this one discovery that infertile eggs kept better than fertile eggs yielded an annual return of about $4,000,000 on an investment of $20,000. Wheeler McMillen, *Too Many Farmers* (New York: William Morrow & Company, 1929), p. 142. There are numerous other examples of high payoffs to the Bureau's programs such as the quarantine system preventing goats with Malta fever and surra infected cattle from entering the country in 1905 and 1906. One of the most fascinating cases of an important scientific breakthrough that had enormous productivity effects occurred following an epidemic of a mysterious and highly fatal disease in Canadian cattle in 1921. F. W. Schofield of the Ontario Veterinary College discovered that the cattle were bleeding to death as a result of eating moldy sweet clover silage. Sweet clover had recently become an important ingredient in silage in both Canada and the United States because of the devastating effect that the European corn borer had on the traditional source of silage. This discovery saved countless cattle from a toxic death; but, in addition, it was the first of a chain of events that led to the development of warfarin, an effective rat poison. Houck, pp. 135-37; Calvin W. Schwabe, *Cattle, Priests, and Progress in Medicine* (Minneapolis: University of Minnesota Press, 1978), pp. 194-95.

[84] Houck, pp.3-4 and 38.

encouraging cooperation for the policy. These efforts financed by the federal government's expenditure of about $1.5 million over five years led to the eradication of contagious pleuropneumonia from the U.S. in 1892. According to Houck, "the United States was the first of the large nations of the world up to that time which, having been once extensively infected with contagious pleuropneumonia, was able to extirpate it completely."[85]

The campaign against tuberculosis represented one of the Bureau's finest hours. In 1900 tuberculosis was still a leading killer in America, with a death rate of over 190 per 100,000 of the population; by 1940 the rate had declined to about 46 per 100,000. According to Schwabe, "the form of the disease that then accounted for up to 10 percent of human pulmonary tuberculosis, and almost all human tuberculosis of other organs, was contracted from cattle rather than from other people. The rate of infection in cattle was then very high."[86]

By 1890, the discoveries of Robert Koch and others provided practitioners with the ability to test for tuberculosis. Armed with this tool, BAI scientists conducted the first US test in 1892—of the 79 animals tested, 30 reacted positively. Other tests also found high rates of infection, but these results need to be discounted because it is likely that herds suspected of being infected were more apt to be tested. In 1917 the TB campaign swung into full gear with special appropriations from Congress and the formation of the Tuberculosis Eradication Division within the BAI. In that year the USDA estimated that about 5 percent of US cattle carried tuberculosis, but that the rate of infection was not uniform across the country. The incidence was greatest in the northeastern and midwestern dairy regions that specialized in providing milk to the larger cities. In many of these areas the infection rate exceeded 40 percent. This posed a high risk to humans, especially young children who were most susceptible to bovine TB. The BAI's campaign involved an extensive testing and inspection program, the destruction of sick animals, and the education of cattlemen as to how to limit the spread of the disease. Between 1917 and 1940 approximately 232 million tuberculin tests had been administered and about 3.8 million animals had been slaughtered. The tuberculosis rate fell from about 5 percent in 1917 to about 0.3 percent in 1940. All 3,071 counties in the US along with the territories of Puerto Rico and the Virgin Islands recorded rates of less than 0.5 percent.[87] In the US, the eradication of bovine TB along with the pasteurization of milk reduced the incidence of bovine caused TB in humans to near zero by the onset of World War II.[88] We can get a rough handle on some of the benefits of the BAI's TB campaign. Assuming that 10 percent of deaths from tuberculosis resulted from the form of the disease contracted from cattle, would have meant that about 15,000 Americans died from this cause in 1900. Given the population of the United States in 1940 of approximately 132 million people, the elimination of the transmittal of bovine TB to humans would have saved about 25,000 lives in that one year. Adding to this the pain, suffering, loss of income, and healthcare

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[85] Houck, pp. 38-47.

[86] Schwabe, p.190, HSUS, p. 58; Schwabe is an astute and well-trained scientist who specialized in the history of veterinary medicine, but his estimates may be high because Wight, et al. note that for an unnamed European country circa 1940 "over 5 percent of all deaths in man from tuberculosis of the lungs and 25 percent of the deaths from nonpulmonary forms are due to bovine tuberculosis." A. E. Wight, Elmer Lash, H. M. O'Rear, and A. B. Crawford, "Tuberculosis and Its Eradication," in *Yearbook of Agriculture, 1942* (Washington D.C.: USDA, 1942), p. 242.

[87] Wight, et al., pp. 237-46 (article pp. 237-49); John R. Mohler, A. E. Wight, W. M. MacKellar, and F. C. Bishopp, "Losses Caused by Animal Diseases and Parasites," *Yearbook of Agriculture, 1942*, p. 110-111; Houck, pp. 347-61.

[88] The spread of pasteurization gained momentum in the teens and the 1920's. Michael R. Haines, "The Population of the United States, 1790-1920," NBER Working Paper Series on Historical Factors in Long Run Growth, No. 56, pp. 36-40.

costs associated with the illness itself, and the improved health and productivity of the TB free animals, would give us a crude approximation of the return from the eradication programs.[89]

IMPROVEMENTS IN LAND INFRASTRUCTURE

In addition to strictly biological innovations, it is possible to increase yields by investing in irrigation, drainage, leveling, terracing, fencing, etc. These types of land-augmenting investments were a major source of productivity growth in a number of Asian nations. But, given the emphasis on labor-saving mechanization that is found in much of the economics literature analyzing US agricultural development, it might come as a surprise to learn that land-augmenting investments greatly exceeded investments in mechanization throughout 19th century America.

From the outset, settlers had to carve their farms out of the forests that covered the eastern third of the United States. Cutting, hauling, and burning trees, along with removing stumps and rocks required an enormous investment that typically exceeded (and often far exceeded) the original purchase price of the land. The general rule for the wooded eastern states was that to clear an acre of farmland required about one month of hard labor of a man and a team of oxen. In the 1850s about 4 million acres of forested land were cleared in the United States every year. In the Midwest alone, about 1.3 million acres a year were transformed from forest to farmland. This required about one-sixth of all farm labor hours in the Midwest.[90] As the line of settlement broke out of the forested lands onto the prairies, the task was easier, at least for a while. The prairie sod was matted with roots and had to be broken. This task was usually performed by contractors who had the proper equipment, and generally cost about one-third as much per acre as clearing trees further to the east.

In addition to clearing and breaking land, huge expenditures were required to build fences. In most areas, cattle and pigs would destroy unprotected crops, so fences were an absolute prerequisite for commercial agriculture. For most farmers, the investment in the labor-intensive tasks of splitting rails along with building and maintaining fences far exceeded expenditures on farm machines.[91] As the line of settlement pushed into the prairies and the Great Plains, the cost of fences soared. In Iowa (an area still reasonably near to sources of lumber) settlers built every manner of wood fences and dabbled with earthen walls and thick hedges.[92] Across the prairies and along the fringes of the Great Plains there was a constant process of experimentation with thorny plants that would repel cattle

[89] The USDA noted that the financial loss to farmers from bovine tuberculosis in 1917 was "conservatively estimated at 25 million dollars." John R. Mohler, A. E. Wight, W. M. MacKellar, and F. C. Bishopp, "Losses Caused by Animal Diseases and Parasites," *Yearbook of Agriculture, 1942*, p. 111. For an example of how this issue should be dealt with see G. Stoneham and J. Johnston, "The Australian Brucellosis and Tuberculosis Eradication Campaign – An Economic Evaluation of Options for Finalising the Campaign in Northern Australia," Bureau of Agricultural Economics Occasional Paper No. 97, Australian Government Publishing Service, Canberra, 1987.

[90] Martin L. Primack, "Land Clearing Under Nineteenth-Century Techniques: Some Preliminary Calculations," *The Journal of Economic History* Vol. 22 (December 1962), pp. 484-97; Martin L. Primack, "Farm Capital Formation as a Use of Farm Labor in the United States, 1850-1910," *The Journal of Economic History* Vol. 26, No. 3 (September 1966), pp. 348-362.

[91] In the West a homestead which could be obtained for less that $20 in fees, would require roughly $1000 to fence, and poorly at that. Walter Prescott Webb, *The Great Plains* (New York: Grosset and Dunlap, 1931), p. 282.

[92] Webb, p. 285.

and pigs. Webb discusses eleven different plants, including osage-orange, bois d'arc, and pyracantha, that had advocates in Texas alone. Some of these "organic fences" proved effective in one area, but not in other areas; most were expensive in seed costs and labor.[93]

The solution was barbed wire which first appeared commercially in the mid-1870s. Between 1874 and 1880 US annual production jumped from 10 thousand pounds to over 80 million pounds. In 1901 the leading manufacturer produced about 300 million pounds. The effect was revolutionary in the prairie and plains states for both farmers and cattlemen. Farmers could now protect their crops and their water supplies from roaming animals—this made farming possible on what became some of the most productive land in the country. The flip side to the coin was the decline in the open range and with it a significant intensification of the cattle industry as ranchers fenced their pastures and began the process of replacing their longhorns with improved breeds of cattle.[94]

Large sections of the western landscape were also transformed by irrigation projects that included the spread of gasoline and electric-powered pumps in California.[95] In 1900 there were about 4 million acres of irrigated land in the US; by 1920 the figure stood at about 20 million acres. Although this only accounted for a relatively small fraction of the total US farmland (or even western farmland), it still represented a major biological achievement. To provide perspective, Japan is held up as the example of a country that followed the biological versus mechanical route. Twenty million acres is about double the total arable land in Japan and three times the total irrigated area in 1993. In two decades the United States irrigated more land than is farmed presently in Japan. Perhaps California provides a better comparison because that state is closer in size to Japan (although the populations were far from equal).[96] Between 1879 and 1939 the area of irrigated farmland in California increased from about 325 thousand acres to about 5 million acres. This is equal to about 73 percent of all the irrigated land in Japan. California's irrigation systems were part of a larger project to channel its rivers and drain its giant inland seas. In the process various public and private agencies built about 1,300 miles of major levees. Farms were crisscrossed with thousands of miles of canals and ditches and massive land planes scraped the earth flat so water would drain efficiently and machines could operate without obstacles. Over one-half million acres of marshes were converted into prime farmland, and several times that acreage was spared the threat of serious flooding. This story of transforming the landscape should add credence to my earlier claim that the history of California agriculture is primarily a story of biological learning and investments.

The California story is far from unique. In the early Colonial period about 215 million acres of wetlands existed in what would become the 48 states. By 1990 about 125 million acres had been drained, with most of this work completed by 1930.[97] Table 2 offers a view of the importance of drainage in seven Midwestern states as of 1930. Twenty percent of the region's farmland had been created out of wetlands, and in Illinois and Indiana about one-third of all farmland had formerly been wetlands. "By 1940 more than half of the crop-producing land in Illinois was artificially drained." A significant portion of Midwestern drainage investments occurred in the 19th century or in

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[93] Webb, pp. 292-94.

[94] Webb, pp. 309-18.

[95] In addition, the diffusion of millions of windmills, along with new methods for drilling (as opposed to digging) wells, allowed farmers and ranchers in the arid western states to obtain at least small quantities of water where before there was none.

[96] Japan contains about 375,000 square kilometers compared to about 400,000 square kilometers in California.

the first decade of the 20th century, and given the technologies of the day, required a huge commitment of human and animal labor. [98]

How important were these investments in improving the farm infrastructure compared to other forms of investment? The seminal work of Robert Gallman on capital formation in the 19th century US economy offers perspective. He finds that the value of land improvements (including land clearing and breaking, fencing, and irrigation and drainage but excluding buildings) represented about one-eighth (12.2 percent) of the total US reproducible capital stock in 1900. Its role was even greater earlier on; in 1840 over one-third (38.4 percent) of domestic capital was land improvement. Gallman's figures also indicate that about one-quarter of all capital formation between 1800 and 1840 was in the form of land clearing and breaking.

The literature typically conceives of agricultural mechanization as representing the most important change in American agriculture after 1840. Gallman's figures help put this view into perspective. It is formally correct to say that investment in equipment increased at a faster rate than that in land improvement between 1840 and 1900. The real value of farm equipment in 1900 was about 17.5 times its 1840 level whereas land improvements increased only 3.9 fold. But comparing these ratios misleads as much or more than it informs. In terms of absolute values and in their changes, land improvements were predominant. In 1900, the value of land improvements represented over half (54 percent) of all reproducible capital in American agriculture whereas equipment made up less than 10 percent. The total value of investment of land improvements between 1840 and 1900 was over four times that in equipment.[99] Bear in mind that Gallman's estimates do not touch on the host of other biological innovations such as improved seeds, better breeds of animals, and new cultural methods that we deal with elsewhere in this paper. Thus, the overall contribution of land-augmenting investments was considerably larger than he reports. Obviously, it is just foolish to consider the 19th century an age of labor-saving innovation, and in the process to downplay the role of land-augmenting changes.

CONCLUSION

The usual story told is that scientific breakthroughs in the realm of biology were more complicated than the breakthroughs required to perfect machines and thus biological—land saving—productivity increases came later, principally in the 20th century.[100] This reasoning may be partially true, but nevertheless it is worth asking what biological, chemical, and other land-augmenting innovations occurred over the course of the 19th and early-20th

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[97] In 1990 the 48 states had a total land base of about 1.9 billion acres, with about 350 million acres devoted to growing crops.

[98] Mary R. McCorvie and Christopher L. Lant, "Drainage District Formation and the Loss of Midwestern Wetlands, 1850-1930," *Agricultural History*, 67:4 (Fall 1993), pp.13-39; Martin Leonard Primack, *Farm Formed Capital in American Agriculture, 1850 to 1910* (New York: Arno Press, 1977), pp. 89-116.

[99] Robert E. Gallman, "The United States Capital Stock in the Nineteenth Century," in Stanley L. Engerman and Robert E. Gallman, eds., *Long-Term Factors in American Economic Growth* (Chicago: University of Chicago Press, 1986), pp. 165-213. Gallman's estimates rely heavily on Primack's work and include the cost of on-farm drainage, but do not include the costs of off-farm drainage projects undertaken by private companies, associations, governments, etc. Thus the construction of most levee and flood control systems is not included. Primack, 1977, p. 91.

[100] This of course implies that we are not dealing with just a derived demand story but that there were independent supply forces also at work governing the pace and pattern of technological innovation.

centuries. The results of this cursory inquiry suggest that land-augmenting innovations had a striking impact on agricultural productivity in the pre-World War II era. These innovations were not just the product of trial and error as practical farmers experimented on the frontier. The fundamental breakthroughs of Pasteur and Koch cleared the way for marvelous changes in the agricultural sector and in human medicine. The revolutionary breakthroughs in food preservation—canning, freezing, chilling, improved dehydration systems, and pasteurization—were all products of 19th century biological innovations. All these innovations increased the demand for agricultural products and improved the quality and variety of the food reaching consumers. In addition, 19th century scientific advances led to a basic understanding of many serious animal diseases, contributing to the development of effective public policy programs to control these diseases.

As we have also seen, there was a systematic worldwide search for parasites that would attack and kill injurious insects and diseases attacking a number of plants. These efforts were matched by another quest—a worldwide search for new plant varieties coupled with widespread selection efforts to develop improved strains of germ stock. In this paper I have focused on how these changes affected the character of the wheat grown in the US and how they made possible a vast expansion of the wheat frontier. Thus, we have the familiar accounts of Turkey, Marquis, Red Fife, and numerous other varieties of wheat that transformed the more arid and more frigid landscapes of the Great Plains.

In the US there was a wholesale change in the quality of livestock over the 19th and early-20th centuries. This again was a direct result of conscious efforts to breed more valuable animals given the changing market conditions. This often was a very labor-intensive process that involved fencing of lands and the end of open range. Breeding associations and registries of select animals were all products of the 19th century. Again, the productivity consequences were significant.

We also need to recognize the importance of new agricultural chemicals in increasing agricultural productivity. Sulfur, Paris Green, Bordeaux Mixture, and numerous other formulations had a profound impact on the productivity of fruit, nut, and vine growers around the world. The large concentrated orchard and vineyard economies of California, much of Western Europe, and certainly pockets of Australia and New Zealand would not have been sustainable without these breakthroughs. The impact of these chemicals extended beyond the fruit and nut industries. In evaluating the impact of biological changes on agricultural productivity, we should not forget one of the worst biological catastrophes to befall Western Europe in the 19th century. Between the mid-1840s and early-1850s, approximately one million Irishmen died and another million emigrated. This was out of a total population of approximately eight million individuals. If the potato blight had occurred roughly forty years later the application of Bordeaux Mixture could have controlled the problem. We must ask, what other crises did not occur because of the availability of this and other biological technologies?

For the most part my summary list of biological changes has focused on crop- or animal-specific changes, but we must also remember that settlement was an evolving process which entailed successive stages of intensification of both land and labor utilization. Hunting and gathering, to grazing, to wheat farming, to mixed farming, and perhaps to dairy operations was a common pattern. In a number of regions, California being a good example, the importance of the change in cropping patterns far outweighed the significance of the changes affecting any given crop. With each stage, the productivity of a given area of land increased even though the average output per acre for any given crop may have remained roughly constant.

In their totality, were these land-augmenting investments more important in increasing agricultural productivity than mechanical changes? Much of the existing economics literature asks such a question and concludes that mechanical changes were far more important. In the process, this literature has consistently relegated biological and other land-augmenting changes to footnotes. Fred Bateman, who did path-breaking work on the sources of productivity growth in the dairy industry, thought that his findings were an exception. Hayami and Ruttan thought that the introduction of Mexican cotton was an exception. It is hard to imagine the wheat frontier moving onto the western Great Plains without the new varieties of hard wheat, yet Parker and Klein's estimates of the sources of grain productivity growth fail to consider the impact of the new varieties. Furthermore, I only added my section on investments in land infrastructure after D. Gale Johnson reminded me of the importance of this issue. It is time to recognize that when we string all of these "exceptions" together they become the rule.

Decomposing technological change into mechanical changes and biological changes may be useful for some purposes, but it also may mislead us. This is because the substitution effect and the scale effects of a given innovation very likely counteracted each other. An invention as seminal as the cotton gin was of course labor saving, but the dynamic impact was to make cotton (a relatively labor intensive crop) more competitive and thus to vastly increase the area planted to cotton. This, in turn, pushed outward the demand for labor and increased the value and intensity of land use. For this reason, it is at least possible that some so-called labor-saving machines actually increased the demand for labor. A number of other machines had land-saving implications. Employing a seed drill required more labor per acre than broadcasting (but probably less labor and less seed per bushel of output). Drilling increased the seed germination rate and reduced the incidence of winter kill. Even the tractor to a large extent was land saving. First, it allowed for more timely work, which helped increase yields and reduce the chance of losses due to weather, etc. Secondly, it released about 85 million acres of cropland used to produce food for draft animals. Thus, an invention that is usually touted for its labor saving characteristics, in fact was one of the most important land-augmenting innovations of all time, increasing the effective US land base that could be used to produce higher value crops for human consumption by over 40 percent! Conversely, many biological innovations were labor saving (at least when we focus on the substitution effects); the impact of Mexican cotton on picking rates offers an important example.

Before closing, there is one more task. That is to ask why have land-augmenting changes been so neglected relative to mechanical changes over the period in question? There are two answers. First, they haven't. The traditional histories of the development of the United States (and I suspect of Canada, Argentina, Australia, and New Zealand) are filled with examples of biological change. This is why I suspect that so much of what I have said is familiar to you. Furthermore, the scientific literature of the day talked of little else. A review of the U. S. Department of Agriculture's *Yearbook* over the second half of the 19th century reveals that roughly two-thirds of all articles dealt with biological topics, and that very few addressed questions of mechanization. In addition, content analysis of the leading U.S. agricultural journals between 1860 and 1910 shows that the space allocated to articles on machinery and tools comprised about one-twelfth the space dedicated to biological topics such as animal husbandry, fertilizer, pests, diseases, and water control.[101] Thus, a reading of both traditional historians and the contemporary accounts reveals an enormous public and private effort to tackle difficult biological problems. Many issues were local and many were maintenance problems, but in their totality these investments had a dramatic impact on agricultural productivity, especially relative to the counterfactual world found in the economics literature that assumes little biological innovation. The 19th century investigations by state agencies and local farmers represent a distinct change in the pattern of human behavior because it is very unlikely that previous generations witnessed similar inquires (they certainly did not have the same level of scientific infrastructure to spearhead these efforts). Thus, the first of my two answers is that the importance of biological and other forms of land-augmenting changes was not ignored by contemporaries or by traditional historians.

The second answer deals with why the economics literature has been so remiss in its understanding of biological changes in the 19th and early-20th centuries. Here, I can only speculate. Enamored by the successes of the Third Green Revolution in increasing output per acre after World War II, may have led some to neglect to ask the proper questions and to pose reasonable counterfactuals. This tendency was probably reinforced by the ease of identifying important and rather glamorous mechanical changes in the 19th century relative to the more difficult task of understanding the host of local biological innovations.[102] The fascination with the induced innovation model, coupled with a misunderstanding of how relative factor prices in the US changed over the 19th and early-20th centuries, probably contributed to a selective searching of the past—researchers found precisely what they were seeking. How else do we explain why so many clever and dedicated scholars repeatedly stubbed their toes on the facts but missed the big picture? For that matter there is probably not a person in this room who is not familiar with the story of Federation wheat. When I discussed the problems of moving the wheat belt onto the Great Plains of the United States and Canada, I suspect that many of you were thinking of the parallel problems in developing wheat varieties suitable for Australia's varying conditions. In this case you already knew the general story of the importance of biological innovations. The trick is to see this as the rule rather as the exception. Why would you expect otherwise when the primary challenge of the century and half before 1940 was to move the agricultural frontier across whole continents!

To close on a positive note, if my general interpretation is correct, we have much work to do to rediscover and quantify the rich and much neglected past of biological change that the Voyages of Discovery set in motion 500 years ago. Integrating this story into the economics literature and working through its implications for our understanding of the process of agricultural development should be a challenging and exciting task. I intend this paper to be a first step. It is meant to set the table and provide the menu. If I may anticipate some of my discussants' remarks, the paper is way too long on statements such "the effect was enormous," and way too short in providing actual estimates of rates of return of one or another innovation. As we all know, this is a difficult business. So, let the hard work begin.

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[101] Olmstead and Rhode, 1993, p.113; Richard T. Farrell, "Advice to Farmers: The Content of Agricultural Newspapers, 1860-1910," *Agricultural History*, Vol. 51 (January 1977), pp. 209-17.
[102] Hayami and Ruttan make this same point. p. 79.

TABLE 1

Purebred Dairy Cattle

Breed	Date First Imported	Founding of Breed Association	Number 1885	1895	1920
Holstein-Friesian	1857	Before 1885	21,138	18,750	528,000
Jersey	Before 1850	1868	51,000	150,000	232,000
Red Polled[103]	1873	1883	No Data	No Data	No Data
Ayrshire	1822	1863	12,867	18,750	30,000
Brown-Swiss	1869	1925	No Data	1,930	40,000[104]
Dutch Belted	1838	1909	No Data	No Data	5,900
Guernsey	1830	1877	4,947	12,547	32,041[105]
Total			89,952	201,977	867,941

103 Red Polled cattle were considered a dual-purpose breed for milk and beef; based on Pirtle's estimate of about 1.8 million grades in 1920, there were probably about 30,000 purebreds in that year.
104 Data for 1926.
105 Data for 1925.

Sources: T.R. Pirtle, *History of the Dairy Industry* (Chicago, Illinois: Mojonnier Bros. Company, 1926), pp. 35-56; Houck, p. 187.

Houck listed "registered purebreds." Alvord estimates that there were roughly "200,000 to 300,000" purebreds in 1890 noting that not all were registered.

TABLE 2

Acreage of Artificially Drained Farmlands in Seven Midwestern States, 1930

State	**Total Farmland (acres)**	**Drained Farmland (acres)**	**(%)**	Drainage Cost per **Acre ($)**
Illinois	30,695,339	9,331,153	31	15.4
Indiana	19,688,675	6,800,417	35	5.31
Iowa	34,019,332	7,334,404	22	12.66
Michigan	17,118,951	2,156,043	13	4.11
Minnesota	30,913,367	2,495,059	8	5.59
Ohio	21,514,059	6,208,870	29	4.51
Wisconsin	21,874,155	423,890	2	6.97
Midwest Total	175,823,878	34,749,836	20	9.30

Source: Mary R. McCorvie and Christopher L. Lant, "Drainage District Formation and the Loss of Midwestern Wetlands, 1850-1930," *Agricultural History* 67:4 (Fall 1993), p. 30.