AGRICULTURAL MECHANIZATION
A Comparative Historical Perspective

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The mechanization of farming in developing countries has been very uneven. In certain parts of Africa, in Java, and in many hilly regions, farmers still till their fields with hand tools even though animal tillage has been common in other parts of the world for thousands of years. While draft animals have completely disappeared in North America, Europe, and Japan, they have been widely accepted in Senegal only in the past few decades. Even in countries where farming is beginning to be mechanized, power tillers and tractors are still restricted to tillage and a few other operations.

This paper discusses the history of mechanization, the major reasons for the wide diversity observed, the options for developing countries in extending mechanization, and the role of government policy in influencing the choice of technology. The emphasis is on the adoption of mechanized techniques in farming systems which are already using animal draft. The issues surrounding the introduction of animal draft where only hand cultivation is practiced are discussed in Pingali, Bigot, and Binswanger (1985). Instead of a summary or conclusions, a set of generalizations is presented in the text.

Economic Influences

The pattern and speed of mechanization is heavily influenced by relative scarcities of capital and labor, and other macroeconomic variables. The responsiveness of invention and innovation to economywide factors has become known as the process of induced innovation (Hayami and Ruttan 1971; Binswanger and Ruttan 1978).

Generalization 1. *The rate and pattern of mechanization are governed substantially by an economy's land and labor endowments, by the nonagricultural demand for labor, and by demand for agricultural products.*

The history of agricultural growth and mechanization in some of today's industrial countries illustrates this generalization. In 1880, factor endowments differed widely among these countries, with Japan having only 0.65 hectares of land per male worker and the United States about forty times as much (see Binswanger and Ruttan 1978, tables 3-1 and 3-2). European countries fell in between, with land in the United Kingdom about twice as abundant as on the continent. These differences in endowments were reflected in massive differences in factor prices. In Japan, a worker had to work nearly 2,000 days to buy a hectare of land, while his counterpart in the United States needed to work only one-tenth of that time.

During the ninety years until 1970, land-labor ratios increased in all countries, especially after 1950. These increases reflect the rapid declines in agricultural labor forces as people moved to industry and off the land. The United States, however, had an increase in agricultural land as well as a reduction in the agricultural labor force, so that differences in land-labor ratios between it and other countries increased. Despite their differences in natural resources, Japan, European countries, and the United States managed to expand their agricultural output by up to 1.7 percent a year. Japan and the continental European countries achieved their rapid growth because yields (output per hectare of arable land) grew at about 1.5 percent a year, or roughly twice as fast as in the United States.

Japan and the United States relied on different technological paths to expand their agricultural output. Research summarized by Hayami and others (1975) and Binswanger and Ruttan (1978) has established that Japan has long emphasized biological, yield-raising technology, much of it supported by heavy investment in irrigation. This emphasis continued with systematic investment in agricultural research initiated after 1868. Until the 1950s mechanization played only a minor role (see table 1). The emphasis on biological technology was supported by conscious government choice: in the late nineteenth century Japan imported machinery from the United States, but did not find it useful. It then hired biologists from Germany to assist in developing its biological research program, which was successful. The United States, however, emphasized mechanical technology even before 1880 (see tables 2 and 3). Although publicly funded biological research was initiated in the 1870s, it did not produce big increases in yields until about 1930, well after the major land frontiers had been closed and mechanization was far advanced.

Successful agricultural growth in various developed countries has therefore capitalized on abundant factors of production: land and mechanization in the United States; labor, land improvements, and biological technology in Japan. Continental Europe also emphasized biological technology before shifting the emphasis to mechanical technology.[1]

Table 1. *Pattern of Agricultural Mechanization in Japan*

(thousands)

Year	*Number of farms*	*Draft and beef cattle*	*Horses*	*Motors*	*Pumps*	*Threshers*	*Rice hullers*	*Power sprayers, dusters*	*Cultivators*	*Power tillers*	*Riding tractors*	*Binders*	*Combines*	*Rice transplanters*
1880	5,500	1,152	1,626	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1900	5,502	1,204	1,542	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1910	5,518	1,259	1,564	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1920	5,564	1,256	1,468	2	2	0.5	0.6	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1931	5,632	1,361	1,477	92	28	56	77	0.2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1939	5,492	1,767	1,168	293	83	211	132	5	3	3	n.a.	n.a.	n.a.	n.a.
1945	5,670	1,827	1,049	424	87	364	177	7	8	7	n.a.	n.a.	n.a.	n.a.
1951	6,145	—[a]	1,112	1,295	92	1,080	460	20	29	16	n.a.	n.a.	n.a.	n.a.
1955	6,027	n.a.	888	2,140	122	2,060	700	87	82	82	n.a.	n.a.	n.a.	n.a.
1960	5,966	n.a.	618	2,799	288	2,651	878	305	791	514	n.a.	n.a.	n.a.	n.a.
1966	5,665[b]	n.a.	396[c]	3,108[b]	n.a.	3,172	1,008[b]	1,126	n.a.	2,725	39	146[b]	n.a.	n.a.
1971	5,342[b]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	2,400	n.a.	3,201	267	582	84	46
1976	4,835[b]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	2,898	n.a.	3,183	721	1,498	428	1,046
1979	4,742	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	2,618	n.a.	3,168	1,096	1,704	747	1,601

n.a. Not available.

a. Continued as beef cattle.

b. Figure corresponds to nearest adjacent year.

c. Figure corresponds to 1963.

Sources: Kazushi Okawa, M. Shinohara, and M. Umemura, *Estimates of Long-Term Economic Statistics of Japan since 1868: Agriculture and Forestry,* no. 9 (Tokyo, 1966); and *Farm Machinery Statistics* (1981).

Table 2. ***Sources of Farm Power in the United States***
(thousands)

Year	Number of farms	Workstock above two years: Oxen	Mules	Horses	Windmills	Steam engines	Gas engines	Tractors (exclusive of steam and garden): Number	Horse-power (millions)	Trucks
1870	2,660	1,319	1,125	7,145	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1880	4,009	994	1,813	10,357	200	24	n.a.	n.a.	n.a.	n.a.
1890	4,565	1,117	2,252	15,266	400	40	n.a.	n.a.	n.a.	n.a.
1900	5,737	960	2,753	15,506	600	70	200	n.a.	n.a.	n.a.
1910	6,406	640	3,787	17,430	900	72	600	10	0.5	0
1920	6,518	370	4,652	17,221	1,000	70	1,000	246	5	139
1930	6,546	n.a.	17,612[a]	n.a.	1,000	25	1,131	920	22	900
1940	6,350	n.a.	13,029	n.a.	n.a.	n.a.	n.a.	1,567	62[b]	1,047
1945	5,967	n.a.	11,116	n.a.	n.a.	n.a.	n.a.	2,354	88[c]	1,490
1950	5,648	n.a.	7,415	n.a.	n.a.	n.a.	n.a.	3,394	93	2,207
1955	4,654	n.a.	4,101	n.a.	n.a.	n.a.	n.a.	4,345	126	2,675
1959	4,105	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1960	3,963[d]	n.a.	2,883	n.a.	n.a.	n.a.	n.a.	4,685	153	2,826
1965	3,356	n.a.	—[e]	n.a.	n.a.	n.a.	n.a.	4,787	176	3,030
1970	2,949	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	4,619	203	2,984
1975	2,767	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	4,469	222	3,031
1979	2,672[f]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	4,350[g]	243	3,045

n.a. Not available.
a. From 1930 onward refers to total workstock on farm.
b. Average horsepower for 1930–34 multiplied by number of tractors in 1930.
c. Average horsepower for 1940–44 multiplied by number of tractors in 1940.
d. After 1960 corresponds to 1969 definition.
e. Discontinued.
f. Figure corresponds to 1978.
g. Tractors over 40 horsepower only.

Sources: Number of farms: up to 1959, U.S. Department of Agriculture, *Century of Agriculture in Charts and Tables;* 1960–79: U.S. Department of Commerce, *Statistical Abstract of the United States* (1980).

Oxen, mules, horses, windmills, gas engines, and steam engines, 1850–1930: W. M. Hurst and L. M. Church, *Power and Machinery in Agriculture* (1933), table 8, p. 12; 1930–79: U.S. Department of Commerce, *Historical Statistics of the United States: Colonial Times to 1970* (1975).

Tractors, horsepower, and trucks, 1870–30: W. M. Hurst and L. M. Church, *Power and Machinery in Agriculture* (1933), table 8, p. 12; 1940–59: U.S. Department of Agriculture, *Changes in Farm Production and Efficiency, 1964 and 1973;* 1960–79: U.S. Department of Commerce, *Statistical Abstract of the United States* (1980).

Generalization 2. *Mechanization leads directly to increased yields only in exceptional circumstances, such as when high-yielding seeds, pesticides, and fertilizers are also used.*[2] *Thus, extra machinery usually substitutes for labor or—where they are already in use—for animals.*

This generalization corresponds to the *substitution view* of agricultural mechanization (Binswanger 1978). It differs from the *net contributor view,* which assumes that more machinery—in particular, tractors—

Table 3. *Production or Sales of Horse-Drawn and Tractor-Drawn Machines in the United States*
(thousands)

Year[a]	*Number of farms*	*Plows* *Horse*	*Plows* *Tractor*	*Harrows (all types)*	*Cultivators*	*Seed drills* *Horse*	*Seed drills* *Tractor*	*Corn surface planters only (hand and horse)*	*Self rake reapers*	*Grain binders*	*Threshers* *Horse (small)*	*Threshers* *Steam (large)*	*Combines*	*Hay making* *Mowers*	*Hay making* *Horse rakes*	*Hay making* *Loaders*	*Hay making* *Stackers*
1870	2,660	865	n.a.	9	89	n.a.	n.a.	22	60	n.a.	23		n.a.	n.a.	81	n.a.	n.a.
1880	4,009	1,326	n.a.	128	318	n.a.	n.a.	69	35	n.a.	10		n.a.	n.a.	96	9	n.a.
1890	4,565	1,249	n.a.	269	445	n.a.	n.a.	132	9	n.a.	11		n.a.	n.a.	115	3	n.a.
1899[b]	5,737[c]	1,075	n.a.	478	505	n.a.	n.a.	208	36	n.a.	1.3	3.6	n.a.	n.a.	216	7	n.a.
1899[d]	n.a.	973	n.a.	478	296	92	n.a.	208	36	233	1.3	3.7	n.a.	399	216	7	12
1909	6,406[e]	1,358	n.a.	701	435	68	n.a.	219	58	129	2.2	8.0	0.5	359	266	35	17
1920	6,518	714	145	604	579	107	3	132	2	100	16.5	4.2	2.7	173	118	32	10
1929	6,512	324	117	540	398	36	16	93	n.a.	65	9.6	1.3	19.6	115	91	26	6
1938	6,527	137	124	351	214	28		57	n.a.	31	2.7	3.6	41.5	76	54	19	1

n.a. Not available.

a. Figures for years before 1920 represent numbers manufactured. The earliest sales figures available are for 1920.

b. Data from U.S. Department of Commerce.

c. Figure corresponds to 1900.

d. Data from McKibben, Hopkins, and Austin.

e. Figure corresponds to 1910.

Sources: 1870–99: U.S. Department of Commerce, *Historical Statistics of the United States: Colonial Times to 1970*. 1899–1938: E. G. McKibben, J. A. Hopkins, and Griffin R. Austin, *Changes in Farm Power and Equipment Field Implements* (Philadelphia: Work Projects Administration, National Research Project, August 1939).

produces higher yields or other gains in output, regardless of the economic environment in which it is introduced. Such a view usually confuses the direct effects of mechanization with the indirect productivity effects of factor savings. For example, in an extensively farmed area of Africa where hoe cultivation is used yields may be low, while in an intensively farmed tractorized region of India yields may be much higher. The yield differences may be caused in part by differences in other inputs, such as fertilizers or seeds. They could also be caused by better tillage in India—but this does not mean that good tillage is achieved only by tractors and cannot be achieved by hand. Examples from Java show that cultivation by hand can be as thorough as by ox or tractor. The lower tillage intensity in Africa may simply reflect the abundance of land: in order to maximize labor productivity, people work thinly over a large area.

Under the substitution view, the profitability of mechanization and its contribution to economic growth depend on the opportunities available to workers (and sometimes draft animals) released from their tasks. Hence the third generalization:

Generalization 3. *Mechanization is most profitable and contributes most to growth where land is abundant, where labor is scarce relative to land, and where labor is moving rapidly off the land.*

Several cases, listed in table 4, illustrate the effects of mechanization on employment. In case 1 unused land is available and mechanization leads to output growth—the more so, the higher the elasticity of final demand.[3] The best example is the United States in the second half of the century: an impressive horse-based mechanization led to massive agricultural growth because land was rapidly opened up and export markets in Europe provided a highly elastic demand for agricultural products. Total farmland more than doubled between 1870 and 1920. Since average farm size stayed roughly constant, total farm employment must have nearly doubled as well. The agricultural work force, far from being displaced, was redeployed within agriculture, along with large numbers of immigrants. Mechanization did not produce higher yields, however; they came later (see table 5) and were linked to fertilizers and biological innovations.

In all these changes, the elastic demand provided by export markets played a crucial role. Without such export possibilities, areas planted, employment, and agricultural output would have expanded less and mechanization would probably have happened more slowly. (If final demand is very inelastic, mechanization could lead to a reduction in agricultural employment even if extra land is available.)

Mechanization can also be induced by labor scarcity arising out of nonagricultural demand for labor (case 2). Production costs rise because

Table 4. ***Direct and Indirect Effects of Agricultural Mechanization***

Forces leading to mechanization	*Immediate consequence of mechanization*	*Indirect effect on agricultural output*	*Indirect effect on agricultural employment*	*Examples*
1. Land available	Labor used on larger areas, production costs drop	*Expands,* and more quickly the more elastic is final demand	*Expands* if demand is elastic; stagnates or falls if demand is inelastic	Nineteenth-century United States
2. Wages rising in response to nonagricultural labor demand	Production costs rise less than in absence of mechanization	*Falls* (or grows more slowly), but by less than in absence of mechanization	*Falls*	United States after 1940; Japan, Europe after 1955
3. Unmechanized technique unprofitable	A new method of production becomes profitable	*Expands,* and more quickly the more elastic is final demand	*Expands,* and more quickly the more elastic is final demand	Pumping in contemporary Asia
4. Subsidies on capital energy	Production costs may drop modestly or stay constant	Small expansion at best	*Falls,* sometimes sharply	Contemporary Brazil, Pakistan, China

wages rise rapidly. Other things being equal, farming output will therefore fall (or grow more slowly), depending on the elasticity of final demand. Farmers mechanize, although they can seldom prevent some increase in their production cost. The best example of these trends comes from the United States after 1940. The use of tractors, combines, and other machines expanded at unprecedented rates (see table 2). Although labor input per acre or per animal had declined a little between 1915 and 1939, it fell sharply after 1940 (see table 5). Agricultural employment also fell substantially, both in absolute and relative terms, and labor was redeployed outside agriculture. The number of workers per farm was stable, while farm sizes grew rapidly from an average of 167 acres in 1950 to 401 acres in 1978. Europe went through equally dramatic changes after 1955.

Cases 1 and 2 show that the labor effects of mechanization depend on the alternatives available to the economy. The Indian Punjab provides an opposite example. The green revolution initiated in the mid-1960s led to sharply increased demand for labor, which caused a big rise in real wages around 1968 (Gupta and Shangari 1979). This in turn led to increased seasonal and permanent migration, primarily from Eastern India.[4] But it also led to the use of more tractors and threshers by Punjab farmers. The combined effect of these developments was a decline in real wages after 1972–73, which brought them closer to the stagnant real wages in the rest of India's agriculture. Because India's

Table 5. ***Productivity Indicators: Labor Hours per Unit of Production and Related Factors, Selected Crops and Livestock in the United States, 1915–78***

Crop and livestock	*1915–19*	*1925–29*	*1935–39*	*1945–49*	*1955–59*	*1965–69*	*1974–78*[a]
Crop							
Corn for grain							
Hours per acre	34.2	30.3	28.1	19.2	9.9	5.8	3.7
Yield (bushels)	25.9	26.3	26.1	36.1	48.7	78.5	87.8
Sorghum grain							
Hours per acre	n.a.	17.5	13.1	8.8	5.9	4.2	3.9
Yield (bushels)	n.a.	16.8	12.8	17.8	29.2	52.9	50.8
Wheat							
Hours per acre	13.6	10.5	8.8	5.7	3.8	2.9	2.9
Yield (bushels)	13.9	14.1	13.2	16.9	22.3	27.5	30.0
Hay							
Hours per acre	13.0	12.0	11.3	8.4	6.0	3.8	3.5
Yield (tons)	1.25	1.22	1.24	1.35	1.61	1.97	2.15
Potatoes							
Hours per acre	73.8	73.1	69.7	68.5	53.1	45.1	38.3
Yield (cwt.)	56.9	68.4	70.3	117.8	178.1	212.8	257.0
Sugarbeets							
Hours per acre	125	109	98	85	51	33	26
Yield (tons)	9.6	10.9	11.6	13.6	17.4	17.5	19.7
Cotton							
Hours per acre	105	96	99	83	66	30	10
Yield (pounds)	168	171	226	273	428	484	462
Tobacco							
Hours per acre[b]	353	370	415	460	475	427	259
Yield (pounds)	803	772	886	1,176	1,541	1,960	2,049
Soybeans							
Hours per acre	19.9	15.9	11.8	8.0	5.2	4.8	3.7
Yield (bushels)	13.9	12.6	18.5	19.6	22.7	25.8	27.8

(continued)

economy was growing slowly, a slower rate of mechanization and a larger volume of migration could have solved the labor shortages in Punjab at a lower capital cost. And the extra employment would have meant that the benefits of the green revolution were shared more widely with workers in poorer regions.

Mechanization can be a powerful stimulus to growth when it makes a new method or crop profitable (case 3). The best example is pump irrigation. Although it is always possible to lift water with animal or human power, it may often not be profitable to do so, even at extremely low wages. The pump therefore enables output to rise—but the size of the increase is determined by the elasticity of final demand. Since the extra production requires extra labor, agricultural employment expands more or less in step with output.

Table 5 *(continued)*

Crop and livestock	*1915–19*	*1925–29*	*1935–39*	*1945–49*	*1955–59*	*1965–69*	*1974–78*[a]
Livestock							
Milk cows							
Hours per cow	141	145	148	129	109	78	48
Milk per cow (pounds)	3,790	4,437	4,401	4,992	6,307	8,820	10,783
Cattle other than milk cows							
Hours per cwt. of beef produced[c,d]	4.5	4.3	4.2	4.0	3.2	2.1	1.4
Hogs							
Hours per cwt. produced[d]	3.6	3.3	3.2	3.0	2.4	1.4	0.6
Chickens (laying flocks and eggs)							
Hours per 100 layers	n.a.	218	221	240	175	97	61
Rate of lay	n.a.	117	129	161	200	219	234
Chickens (farm raised)							
Hours per 100 birds	33	32	30	29	23	14	12
Hours per cwt. produced[d]	9.4	9.4	9.0	7.7	6.7	3.7	3.0
Chickens (broilers)							
Hours per 100 birds	n.a.	n.a.	25	16	4	2	0.6
Hours per cwt. produced[d]	n.a.	n.a.	8.5	5.1	1.3	0.5	0.2
Turkeys							
Hours per cwt. produced[d]	31.1	28.5	23.7	13.1	4.4	1.3	0.6

n.a. Not available.
cwt. Hundred weight.
Note: Labor hours per acre harvested include preharvest work on areas abandoned, grazed, and turned under.
a. Preliminary.
b. Per acre planted and harvested.
c. Production includes beef produced as a by-product of the milk cow enterprise.
d. Liveweight production.
Source: Economics, Statistics and Cooperative Service-Economics.

The pace of mechanization is influenced by three other economic factors: capital scarcity and energy costs, farm size, and subsidies.

Capital scarcity and energy costs. Poor societies have smaller capital stocks than rich ones, and the cost of capital (in terms of labor) is higher. High capital costs retard mechanization in several ways. First, they reduce the profitability of all forms of agricultural investment, including land improvements, irrigation, animals, and buildings. Second, they may cause farmers to allocate whatever investment funds are available away from mechanical inputs. This trend will be stronger the more expensive and long-lived the mechanical inputs are and the easier it is to produce other forms of capital (such as land improvements) by hand. A third effect, discussed in detail in the next section, is that higher capital costs produce a bias in mechanization toward power-intensive operations. Finally, higher capital costs influence the design of machines; if repair costs are relatively low, designs emphasize repair over durability.

Generalization 4. *High capital costs (relative to labor) retard mechanization and lead to selective emphasis on power-intensive operations. Machinery design adjusts to high capital costs by lack of convenience features, simplicity, and reduced durability.*

Energy is only one of the costs of using machines. Capital and maintenance costs are often larger. Since the profitability of machines—their comparative advantage—is tied closely to labor costs, expensive energy is likely to retard mechanization much more in countries with cheap labor.

Farm size. The size of the average farm is largely a reflection of the scarcity of land relative to labor and thus need not be an independent influence on the pace of mechanization. Mechanization can certainly facilitate the growth of large farms, however, as it did in the United States after 1940 and later in Western Europe.

Generalization 5. *Mechanization is the main facilitator of the trend toward bigger farms.*

This goes along with another lesson from historical data and contemporary experience:

Generalization 6. *Large farms adopt new forms of machinery considerably faster than small farms.*

Because larger farms offer more collateral, they make it easier to borrow to invest in new machinery.[5] In addition, some (but not all) mechanization is subject to genuine economies of scale: it is technically more efficient to design a large rather than a small machine. Even machines invented in countries with abundant labor (and therefore smaller farms) were first developed for the largest farms, because they had the lowest costs of capital relative to labor.[6] The market for machines expanded to smaller farms only when labor costs rose or capital became more abundant. In the history of engineering, technical developments have often been embodied in smaller and smaller machines.[7] Japan, in particular, has developed many machines for small farms and plots.

For certain operations, mechanization spreads to small farms when machinery can be rented rather than bought. For a rental market to be established, the optimal farm size for owning a machine must be bigger than that of numerous small farms. In addition, it is easier to establish rental markets for operations that do not need to be done on all farms at the same time: threshing and milling are examples. It is thus no accident

Table 6. ***Ownership and Use of Farm Equipment in the Philippines, 1971***
(thousands)

Type of equipment	*Number of farms reporting*	*Number of machines owned by farm operator*	*Number of farms using machines*		*Ratio of renters to owners*
			Owned fully or party	*Rented or provided by landlord*	
Total number of farms	2,355	—	—	—	—
Plows	1,170	1,511	1,366	129	0.09
Harrows	887	1,069	1,031	94	0.09
Tractors	11	16	12	78	6.50
Stripping machines, crushers, shellers	16	19	18	85	4.72
Harvesters and threshers	14	26	16	132	8.25
Power-producing machines	5	7	6	3	2.00
Carts and wheelbarrows	262	292	306	46	0.15
Motor vehicles	14	19	15	69	4.60
Sprayers	79	90	89	61	0.69

Source: National Census and Statistics Office, *Philippine Census of Agriculture 1971* (Manila: National Economic and Development Authority, 1971).

that rental markets for threshing machines were well established in the nineteenth century in the United States and are now common all over Asia (Gardezi and others 1979; Walker and Kshirsagar 1981). The contract-hire system for combines in the United States illustrates the problem of synchronized timing. The contractors achieve higher rates of machinery utilization by migrating to follow the harvest from the Texas-Oklahoma area to the northern states, where harvesting takes place months later. Milling rice for home consumption can also be done over a long period, and in Asia it is common for a mill owner to "rent" his machine to customers. Rental markets for land preparation, with the use of animals or tractors, were once common in the United States, when plows were scarce, and in Europe. Such rental markets are now common in Asia wherever tractors or power tillers have penetrated.

These characteristics of rental markets are confirmed by some data for tractor rentals in South Asia and machinery rentals in the Philippines (see table 6). The Philippine data show that most farmers own their animals, carts, plows, and harrows. Harvesting and threshing equipment, tractors, and motor vehicles, however, are used on about five to seven times more farms than own them, which indicates that rental markets are extremely well developed.

Generalization 7. *Where rental markets are fairly easy to establish, farm size has much less influence on the size of machines.*

Subsidies. Subsidies may speed up mechanization (case 4). Because the direct effects of mechanization on yields are small, however, any effect of subsidies on agricultural output must be an indirect one that arises from the cost reduction made possible by machines. But when mechanization is not spontaneously driven by some form of labor scarcity, the impact on production costs is not large; the output effects of subsidies therefore cannot be large either.

When mechanization is caused by subsidies, reductions in the agricultural work force can be substantial. Unlike in cases 1 and 2, workers who lose their jobs will find only inferior alternatives, and some may remain unemployed; this redeployment of labor is not a productive benefit, but a loss. Nor is there any potential relief from drudgery for the redeployed workers, since their inferior work options may in fact entail more drudgery.

Patterns of Mechanization

The most dramatic aspect of mechanization is the shift from one source of power to another. In ancient China cattle began to replace human labor more than 3,200 years ago. Between the second and fourth century A.D. fairly widespread use of water power is reported from China for rice pounding, grinding, and water lifting (Liu 1962). Water power was widely used for milling purposes in Europe during the Middle Ages; at about the same time wind power is reported to have been used in China and Europe as well. In nineteenth-century Europe and North America, oxen were displaced by horses, which provided power for many mechanical devices from about 1850 to as late as 1965.

Steam engines were widely used for only about fifty years between 1870 and 1920. After 1900 they were rapidly displaced by internal combustion engines and electric motors. Tractors came into widespread use in North America after about 1920, but coexisted with horses for roughly twenty-five to thirty years. Except for Great Britain, where tractors began to be adopted in the 1930s, the tractorization of European and Japanese agriculture was delayed until about 1955, after which it happened very quickly (table 7).

The emphasis on shifts in power sources, especially the shift to tractors, can cause misunderstandings about which operations are the most likely candidates for mechanization in developing countries. This section therefore discusses mechanization in terms of operations and pays only occasional attention to power sources. Most of the evidence comes from machinery stock data; though lacking detail, no other data can give so comprehensive a picture over long periods of time.[8]

Operations can be grouped in terms of the intensity with which they require power (or energy) relative to the control functions of the human mind (or judgment). Regardless of the stage of mechanization, new power sources are always used first for power-intensive operations. Furthermore, it appears that the price of labor matters less for the mechanization of power-intensive operations than for control-intensive

Table 7. *Growth in Number of Tractors in Selected Countries*

(thousands)

	Japan									Korea				
Year	*Two wheel*	*Four wheel*	*Germany*	*Denmark*	*France*	*United Kingdom*[a]	*United States*	*Spain*	*Yugoslavia*	*Two wheel*	*Four wheel*	*India*	*Mexico*	*Philippines*
1920	n.a.	n.a.	n.a.	n.a.	n.a.	10	246	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1930	n.a.	n.a.	n.a.	n.a.	27	30	920	n.a.	n.a.	n.a.	n.a.	n.a.	4	n.a.
1938–39	3	n.a.	30	4	36	55	1,545	3	n.a.	n.a.	n.a.	n.a.	5	0.2
1945–47	8	n.a.	69	4	77	244	2,613	5	n.a.	n.a.	n.a.	5	n.a.	1
1950	16	n.a.	140	17	137	325	3,394	10	6	n.a.	n.a.	9	23	n.a.
1955	82	n.a.	462	58	305	436	4,345	25	10	n.a.	n.a.	21	n.a.	n.a.
1960	514	n.a.	857	111	680	456	4,688	39	36	1	n.a.	31	55	8
1965–66	2,725	39	1,164	161	996	482	4,787	148	45	11	n.a.	54	n.a.	n.a.
1970	3,201	267	1,371	175	1,230	514	4,619	260	80	44	0	148	91	11
1975–76	3,183	721	1,425	185	1,363	541	4,469	379	226	60	1	228	102	n.a.
1979	3,168	1,096	1,456	190	1,430	508	4,350	492	385	n.a.	n.a.	310	114	n.a.

n.a. Not available.

a. Great Britain and Northern Ireland.

Sources: Binswanger (1984), tables 3, 9, 12, 13, 14, 16, 18; Organisation for Economic Co-operation and Development, *Development of Farm Motorization and Consumption and Prices of Motor Fuels in Member Countries* (Paris, 1962); and Food and Agriculture Organization, *Production Yearbook,* various issues.

Table 8. ***Machinery Patterns in France***
(thousands)

Year	*Plows*	*Cream separators*	*Threshers*	*Root cutters*	*Hay and straw presses*	*Pick-up trucks*	*Sowing machines*	*Fertilizer distributors*	*Sprayers of traction*
1852	2,578	n.a.	60	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
1862	3,206[a]	n.a.	101	28	n.a.	n.a.	11	n.a.	n.a.
1882	3,267	n.a.	211	n.a.	n.a.	n.a.	29	n.a.	n.a.
1892	3,669	n.a.	234	n.a.	n.a.	n.a.	52	n.a.	n.a.
1929	1,190[b]	666	204	n.a.	10	74	322	119	142
1937	n.a.	n.a.	152	n.a.	9	n.a.	n.a.	n.a.	n.a.
1941	n.a.	n.a.	141	n.a.	9	n.a.	n.a.	n.a.	n.a.
1946	1,325	626	206	1,007	12	n.a.	385	151	85
1950	1,385	686	218	1,099	17	n.a.	410	165	104
1955	1,427	696	215	1,152	26	n.a.	447	221	122
1960	n.a.	672	191	1,152	33	n.a.	514	321	153
1965	n.a.	n.a.	122	n.a.	n.a.	n.a.	n.a.	n.a.	223
1970	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	304
1977	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	406

n.a. Not available.
a. Includes 794 improved plows.
b. Double-sided plows only after 1929.
c. Includes motor-driven mowers.
d. Only self-propelled combines.

ones—that is, it often pays to move to a higher stage of mechanization in power-intensive operations, even at low wages, when mechanization of control-intensive operations is not profitable. The rest of this section provides support for the following:

Generalization 8. *When new power sources become available, they are initially used only for selected operations for which their comparative advantage is greatest. Power-intensive operations are shifted most rapidly to new power sources. Control-intensive operations are shifted to the more mechanized techniques when wages are high or rapidly rising.*

Power-intensive processing and pumping. Milling, threshing, chopping, sugarcane crushing, pumping of water, and the like are extremely power-intensive but need little control. Moreover, both stationary and mobile sources of power can be used for them. Among the stationary sources, water was first used for milling, pounding, and grinding in the first century B.C. in China. Water-powered milling was also invented in France in the fourth century A.D., though not until the twelfth century was it adopted throughout Europe. Wind power has historically been used almost exclusively for milling and for lifting small amounts of

Reaper/ binders	Mowers	Motor mowers	Combines	Hay balers	Potato diggers	Sugar beet diggers	Rakes	Tedders	Milking machines
n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
9	9	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	6	n.a.
n.a.	19	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	27	n.a.
23	39	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	51	n.a.
420	1,389	n.a.	n.a.	n.a.	60	13	739	354	4
341	n.a.	n.a.	0.3	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
481	1,279	n.a.	0.3	n.a.	n.a.	n.a.	733	448	n.a.
501	1,373[c]	n.a.	n.a.	n.a.	67	10	740	n.a.	n.a.
529	1,470[c]	n.a.	5	n.a.	77	11	785	n.a.	46[f]
560	1,547[c]	n.a.	18	17	90	12	839	n.a.	80
534	n.a.	97	50	51	91	15[e]	n.a.	n.a.	124
361	n.a.	104	102	169	100	20	n.a.	n.a.	186
133	n.a.	105	133	292	92	25	n.a.	n.a.	283
n.a.	n.a.	84	148[d]	445	n.a.	n.a.	n.a.	n.a.	392

e. Includes only diggers up to 1960 and only complete harvesters from 1965 on.
f. Figure corresponds to 1951.
g. Reaper binders only after 1937.
Source: Ministère de l'Agriculture, *Statistique Agricole (Retrospectifs 1930–1957)* (Paris, 1959); and *Statistique Agricole de La France* and *Statistique Agricole Annuelle* (Paris: Imprimerie Nationale), various issues of each.

water. Mills and threshers were the most common users of steam power in the late nineteenth and early twentieth century in both Europe and the United States.

Mechanical threshing based on human power, but especially on horses, became widespread in the United States and Britain as early as 1830. By 1850 virtually all grain in the United States was threshed by large mechanical threshers, which went from farm to farm during the winter months. Rental markets were extensive. By 1852 the number of threshing machines in France had already reached nearly one-third of its peak 1929 level (see table 8), though they spread more slowly in Germany. Except for some animal-drawn primary tillage, stationary machines for power-intensive operations preceded all other forms of mechanization in Japan.

In South Asia animals have long driven Persian wheels, sugarcane crushers, and oil crushers. Animals used in these operations are increasingly being replaced by diesel and electric engines. In India in 1972 the number of stationary engines for power-intensive operations was about twenty times that of tractors (see table 9). And in China (table 10) the number of threshers alone exceeded the combined total of tractors and power tillers, even in 1980. In all of Asia mechanical rice milling for large trade quantities had already been introduced in the late nineteenth

Table 9. ***Pattern of Farm Mechanization in India***
(thousands)

Year	*1945*	*1951*	*1956*	*1961*	*1966*	*1972*
Draft animals	59,333	67,383	70,690	77,986	78,517	80,137
Persian wheel	n.a.	n.a.	n.a.	600	680	638
Oil Pumps	12	83	123	230	471	1,558
Electric pumps	9	26	47	160	415	1,618
Tractors	5	9	21	31	54	148
Plows						
Bullock						
Wooden	27,306	31,796	36,142	38,372	39,880	39,294
Iron	487	931	1,376	2,298	3,521	5,359
Tractor	n.a.	n.a.	n.a.	n.a.	n.a.	57
Other tillage implements						
Bullock	n.a.	n.a.	n.a.	n.a.	2,724	17,119
Tractor	n.a.	n.a.	n.a.	n.a.	n.a.	111
Sugarcane crushers						
Power	9	21	23	33	45	87
Bullock	481	505	545	590	650	678
Oil extractors						
Above 5 seers[a]	n.a.	243	66	78	74	40
Less than 5 seers[a]	n.a.	20	212	172	159	76
Shellers						
Indigenous	n.a.	n.a.	n.a.	n.a.	n.a.	175
Power	n.a.	n.a.	n.a.	n.a.	n.a.	16
Threshers						
Indigenous	n.a.	n.a.	n.a.	n.a.	249	n.a.
Power	n.a.	n.a.	n.a.	n.a.	n.a.	207
Chaff cutters						
Rotary	n.a.	n.a.	n.a.	n.a.	4,729	n.a.
Power	n.a.	n.a.	n.a.	n.a.	n.a.	161
Transport						
Bullock	8,483	9,862	10,968	12,072	12,695	12,960
Tractor	n.a.	n.a.	n.a.	n.a.	n.a.	55
Seed drill/planter						
Bullock	n.a.	n.a.	n.a.	n.a.	1,135	4,047
Tractor	n.a.	n.a.	n.a.	n.a.	n.a.	34
Sprayer/duster	n.a.	n.a.	n.a.	n.a.	211	413

n.a. Not available.
a. A seer equals about 2.05 pounds.
Source: Directorate of Economics and Statistics, *Agricultural Situation in India* (1976), p. 141; and Central Statistical Organization, *Statistical Abstract of India 1975,* pp. 57–61.

century, usually based on steam and later on internal combustion engines. Smaller rice mills have swept across Asia since the 1950s; it is hard to find villages where rice is still pounded by hand. Thus mechanical milling is even more widespread than mechanical threshing. But where the green revolution raised wages and increased harvests (as in Indian Punjab, Philippines, and central Thailand), the small threshers were rapidly adopted once efficient designs were available. The new threshers are now also penetrating into other South Asian regions (Walker and

Table 10. ***Patterns of Mechanization in China***
(thousands)

	Four-wheel tractors	*Garden tractors*	*Threshers*	*Combines*	*Farm trucks*
1957	n.a.	n.a.	n.a.	2	4
1962	55	n.a.	n.a.	6	8
1965	73	4	110	7	11
1970	125	78	455	8	16
1975	345	599	1,553	13	40
1979	667	1,671	2,328	23	97
1981	790	2,030	n.a.	n.a.	n.a.

Note: In 1980 there were 560 tractor trailers and 36,000 wheelbarrows with rubber tires. In 1979 draft animals, including young stock, totaled 94,591, broken down as follows: oxen, 52,411; cows used for draft, 558; water buffaloes, 18,377; horses, 11,145; donkeys, 7,473; mules, 4,023; and camels, 604.

Sources: Ministry of Agriculture, Animal Husbandry, and Fisheries, *Agricultural Yearbook of China, 1980* and China Academy of Agricultural Engineering.

Kshirsagar 1981). As with earlier American and European experience, mills and threshers are usually rented.

Generalization 9. *The mechanization of power-intensive processing and pumping operations always precedes the mechanization of harvesting and crop husbandry operations and can be profitable at low wages.*

Land preparation. Unlike the power-intensive operations, land preparation requires mobile sources of power, such as animals, tractors, or power tillers (hand tractors). Of all land preparation operations, primary tillage (breaking soil, often combined with turning its top layer) is the most power-intensive. It is also usually the first use of a new source of power. Investment in animal-drawn harrows occurs later and is usually much less than investment in plows. The widespread use of modern steel harrows in the United States was delayed until the 1880s, roughly fifty years after the massive shift to cast iron and steel plows. When tractors were introduced, they began to be used universally for primary tillage, while animals continued to be used for other types of soil preparation.

Generalization 10. *Primary tillage is one of the first operations to be mechanized when a new source of mobile power becomes available. Secondary tillage operations often continue to be performed by the old power source for a long period.*

Transport. Carrying loads is the earliest use of domesticated work animals, even preceding tillage. Shifts to animal-drawn sleds or carts follow, especially when marketed quantities increase. The cart and plow are the basic farmer-owned implements of early animal-drawn mechanization (see table 11).

When mechanical power becomes available, it is soon used for farm-to-market transport. Early tractors had no tires and in the 1920s were rarely used for farm-to-market transport in the United States or Great Britain. Instead, mechanizing farmers bought both tractors and trucks at about the same time. That also happened in Mexico after 1960 (see table 12). For on-farm transport, American farmers continued to use horses well into the 1940s. In Asia, where farms are rarely big enough to support the purchase of a truck, farm-to-market transport is increasingly done by hired trucks or tractors. Rubber tires have given tractors a strong comparative advantage in most forms of transport.

Generalization 11. *Transport, along with primary tillage, is one of the first uses of new sources of mobile power. Where distances are long, trucks rather than tractors are used for farm-to-market transport.*

Harvesting. Without machinery, harvesting is very labor-intensive. Different crops vary widely, however, in the type of labor required—that is, in their power- and control-intensity. Harvesting of root crops is probably the most power-intensive, although it still requires significant

Table 11. ***Pattern of Farm Mechanization in Senegal***
(thousands)

Year	*1950*	*1955*	*1959*	*1965*	*1970*	*1975*
Animals						
Horses	n.a.	n.a.	98	160	200	210
Asses	n.a.	n.a.	78	147	185	196
Work oxen	n.a.	n.a.	1[a]	1	2	8
Tractors	n.a.	n.a.	0.2	n.a.	0.5	0.4
Plows	0.1	0.6	2	7	8	39
Hoes	0.8	2	4	36	102	219
Harvestors/threshers	n.a.	n.a.	0.1	0.1	0.3	0.1
Carts						
Horse	n.a.	n.a.	1[a]	18	23	38
Ox	0.3	3	6	5	5	14
Ass	n.a.	n.a.	0	0.3	6	14
Sowing machines	11	31	46	94	120	189
Groundnut lifters	n.a.	n.a.	0	6	18	42

n.a. Not available.
a. Figure corresponds to 1960.
Sources: Tractors and harvester/threshers: Food and Agriculture Organization, *Production Yearbook*, various issues. Work oxen, 1959–65: World Bank, *Senegal: Tradition, Diversification, and Economic Development* (Washington, D.C., 1974). Others: up to 1955, Y. Marie-Saite, *La Culture attelée au Sénégal* (Dakar: Direction de l'aménagement, 1963); 1959 onward: Ministère du Plan et de l'Industrie, *Situation Economique de Sénégal*, various issues.

control. At the other extreme, cotton, fruit, and vegetables require intensive control: in the case of apples, the threat of damage is so large that their harvesting has still not been successfully mechanized.

During the nineteenth century many attempts were made to develop harvesting machinery in Europe and the United States (van Bath 1960; USDA 1940). Reapers for small grains became widely adopted in North America after 1850, with grass mowers for the dairy regions following shortly afterward. But in France and Germany these machines did not make a substantial impact until 1890 or 1900. This time lag cannot be explained by lack of engineering knowledge in Europe: the same countries were using mechanical threshers for virtually all their crops and seed drills had already been widely adopted. The difference was that labor was more abundant in Europe, farms were smaller, and the harvesting machines were therefore not profitable.

The United States started moving from reapers to wheat binders in the 1870s and to corn binders in the 1880s. These changes coincided with, or even preceded, the development of modern harrowing technology: spring tooth harrows and disk harrows. European farmers did not adopt reaper-binders until the first decade of the twentieth century (Bogart

Table 12. ***Pattern of Farm Mechanization in Mexico***
(thousands)

Year	*1930*	*1940*	*1950*	*1960*	*1970*
Number of holdings	858	1,234	1,383	1,365	1,020
Work animals	n.a.	n.a.	3,920	3,476	4,150
Engines[a]	n.a.	9	14	18	47
Electric motors	n.a.	n.a.	n.a.	n.a.	28
Tractors	4	5	23	55	91
Plows					
Indigenous	904	925	1,135	1,100	916
Iron	n.a.	720	1,128	1,286	1,301
Harrows and cultivators	n.a.	102	240	308	387
Threshers (fixed)	4[b]	2[b]	3[b]	5	3
Shellers					
Engine	n.a.	2	3	5	13
Hand	n.a.	4	5	9	18
Forage choppers	n.a.	2	3	6	6
Carts	106	131	175	211	161
Trucks	4	6	18	40	104
Seed drills	26	27	60	93	122
Mowers/reapers	8	5	8	10	12
Hay balers	n.a.	2	3	5	12
Combines	n.a.	n.a.	n.a.	4	7

n.a. Not available.
a. Fixed and movable engines.
b. May include some combines.
Source: Dirección General de Estadística, *Censos Agrícola: Ganadero y Ejidal,* decennial.

1942). In Japan reaper-binders had a perceptible impact only after 1967, almost a hundred years after the United States and a good thirty years after Japan started mechanizing pumping, threshing, and winnowing in earnest. Again, technological ineptitude in Japan cannot have been the cause for such long delays.

Practical development of horse-drawn harvesting combines started in the 1860s in California, where labor was extremely scarce. By the 1880s combines drawn by between twenty-four and forty horses reaped ten to fifteen hectares a day in California. In the 1890s combines drawn by steam tractors had a capacity of up to twenty hectares of wheat a day (van Bath 1960; USDA 1960), but combines did not spread beyond California until 1914. They did not appear in Great Britain until 1928, nor in most of continental Europe until 1935, and not in Japan until about 1970.

At each level of mechanization, machines for harvesting maize have tended to lag a few years behind those for small grains. Hay harvesting equipment, horse rakes, and tedders became important during the American Civil War of the 1860s and remained so until World War II. In France in 1892, hay-raking machines had not reached 10 percent of their 1955 peak number. Hay loaders became widely used in the United States after 1880 but did not spread in continental Europe until after World War II, only to be quickly replaced by hay balers and other more sophisticated machines.

Most of the animal-drawn harvesting machines derived their power from horses. Oxen could not be used successfully because sufficient power could be generated only at the higher speed of horses. The demise of the oxen in American and European agriculture was largely the result of their inability to work harvesting machines. When tractors became available, they could pull harvesting machines with only minor modifications. Nevertheless, horses did not lose their comparative advantage, even in harvesting, for some years.

Generalization 12. *Because mechanization of harvesting is directly dependent on labor costs, it is rarely profitable in low-wage countries. The higher the control intensity of the operation, the higher must labor costs be to warrant using a machine.*

Crop husbandry. Weeding and cleaning of crops, fields, and orchards are control-intensive operations. In animal systems, people go on weeding by hand long after the introduction of the plow and cart—until rising wages make herbicides profitable. Wages are so low in South Asia that, except for tea plantations, it is still cheaper to weed by hand than to use herbicides (Binswanger and Shetty 1977). Mechanical weeding between the rows with animals becomes feasible only when line seeding is practiced. Inter-row cultivation also tends to be performed by animals long after tractors are used for tillage.

Generalization 13. *Crop husbandry shifts to new sources of power only after tillage, transport, threshing, and seeding have done so.*

Seeding and planting. Animal and tractor-drawn machines are capable of greater precision than hand methods for only a few agricultural operations, especially seeding and planting. Mechanical means of seeding may lead to modest direct improvements in yields and may be attractive in land-scarce countries with intensive farming. The first seed drills were developed in China and Mesopotamia in the third millenium B.C. (van Bath 1960). The Mesopotamian drill required three workers—one to drive the oxen, one to put grain in the hopper, the third to hold the drill steady. It was apparently possible to use this instrument profitably only in the fertile soil of Mesopotamia, where high yields could be achieved and labor was abundant. The drill soon fell into oblivion.

Between the sixteenth and nineteenth centuries, farmers in Europe tried to design better seed drills for small grains. Seed drills with mechanical dribbling devices were commonly used in the United States in the 1860s and 1870s. In continental Europe their use started slightly later, became widespread in the late nineteenth century, and was followed a decade later by maize drills and cotton seeders.

The use of seed drills similar to the Mesopotamian drill has been growing rapidly in India since 1966 (see table 9). In Senegal, where animal traction is primarily a post-1945 development, seed drills have become one of the most popular implements (see table 11). Improved seed drills, with mechanical dribbling of seeds, are becoming popular in South Asia and are one of the more successful machines in Mexico (see table 12). In all these cases it is not labor saving which leads to their success, but the improvement in yields, the saving of seed, and the ease of interculture. For most developed and developing countries for which data are available, the spread of seed drills is paralleled by the spread of inter-row cultivators or, at an earlier stage, simple animal-drawn hoes or blade harrows for interculture.

Generalization 14. *In labor-abundant countries, seeding of grains tends to be mechanized before grain harvesting, but the order is usually reversed when labor is scarce.*

Fertilizer and pesticide placement. Although fertilizer can be spread by hand, it produces higher yields if it is dispensed precisely. Thus, animal-drawn machines for spreading fertilizer were developed as fertilizer use increased. Since fertilizer was more intensively used in Europe in the interwar period, fertilizer distributors were common there. Large cart-mounted barrels for spreading liquid cow manure were also widely used, as were elaborate pumping systems. By contrast, in land-abundant North America the use of liquid manure was virtually unknown.

Liquid pesticides cannot be applied without at least a hand pump. Even for pesticides in dust form, mechanized dusters achieve higher precision and reduce waste. Sprayers were developed at the same time as pesticides. In France, for example, spraying carts were widely used in vineyards in 1929. But in Japan hand-carried power sprayers for rice and other crops became popular only with the development of a much wider range of pesticides after World War II. Such power sprayers are now used throughout Asia, often hired on a contract basis.

Generalization 15. *The growth of hand and power sprayers is driven by the availability and use of pesticides and is widespread even at very low wages. Higher wages lead to the use of larger sprayers which may be animal- or tractor-drawn.*

Assessment. The selective use of new power sources (particularly tractors) for power-intensive operations has often been viewed as a sign of inefficiency. Since a farmer makes a huge investment in a tractor, why not use it for all operations? U.S. studies carried out in the 1920s and 1930s show clearly that there is nothing inefficient in the selective use of tractors for power-intensive operations. As long as agricultural wages were relatively low, large farmers found it more efficient to maintain a tractor and truck along with some horses. Horses did virtually all the jobs for which power was not the overriding input. Each power source specialized in the tasks for which it had the greatest comparative advantage. Tractors were mainly used for tillage and as power sources for stationary machines such as threshers, saws, silo fillers, and choppers. The same pattern of tractor use was common in Europe until about 1960 and is now common in South Asia, Southeast Asia, and China. The only differences are that direct power takeoff has replaced the belt and pulley and that tractors are now more frequently used for transport. Although modern tractors are more efficient than prewar ones, wages in Asia are much lower than in the prewar United States. Asian countries are therefore likely to make continued use of animals along with tractors, until rising wages make the animals' drivers, and thus the animals, too expensive.

The Speed of Mechanization

During the twentieth century and especially since World War II, the speed with which farmers adopt new machines has quickened. In Japan, for example, the number of motors, threshers, and hullers increased five- to tenfold between 1939 and 1955. Power tillers grew from less than 100,000 to more than 3 million between 1955 and 1975. Binders, combines, and rice transplanters spread even more rapidly in the 1970s.

Such spurts are not unique to Japan. Continental Europe experienced many similar surges in 1955–70. In Taiwan, after 1968, it took only about a decade to shift primary tillage completely to power tillers.

Central Thailand, in about fifteen years from the late 1960s, went over entirely to tractor tillage with locally designed power tillers and small four-wheel tractors. The adoption of small paddy mills in Southeast Asia was also very quick.

Rapid change has not been confined to the twentieth century. In the United States threshers spread enormously from 1830 to 1850 once satisfactory designs were available (USDA 1940). The same seems to have happened in Europe. However, the speed of change cannot be captured by historical statistics that focus on power sources at a national level; it is observed in operations at a regional level. For example, the growth of tractors in the United States was spread over a fifty-year period with occasional spurts, but once tractors became available, they took over primary tillage within a much shorter time. Their further growth involved shifting extra operations from horses to tractors. Today few farms in the Indian Punjab plow land with animals, thresh wheat by hand, or use Persian wheels. This is only fifteen years after tractors, threshers, and pumps became an important factor in Punjab farming. The aggregate Indian data in table 9 hide these facts because animals continue to be used for other work, even in Punjab, and because many other regions have not yet shifted massively to tractor plowing or mechanical threshing.

In the case of threshers, adoption cycles have always been fairly short. Once locally adapted designs are available, the cost advantage seems to be overwhelming. For other machines, the explosive growth of the postwar period must be understood as a response to unprecedented rates of growth in agricultural wages. This section therefore concludes with two generalizations.

Generalization 16. *Where cost advantages are large or change rapidly, individual operations are mechanized very quickly. Within smaller regions, adoption periods are often as short as ten to fifteen years.*

This speed of adoption implies directly:

Generalization 17. *In market economies, supply bottlenecks in the production, distribution, and servicing of machines are rarely a major cause of their slow adoption.*

The Process of Mechanical Invention

The previous sections imply:

Generalization 18. *Neither power sources nor the basic engineering solutions for particular farming tasks are very sensitive to variations in soil and weather. However, the power sources must be embodied in specific machines and the basic engineering solutions adapted to different* *environments. Both agroclimatic factors (soil, terrain, rainfall) and economic factors (land, labor, capital, farm size, and materials available) require adaptive innovation on a scale that has been vastly underestimated.*

The extent of adaptive innovation required is best illustrated by patent statistics from the United States, which Evenson (1982) has put together on a regional basis. For other developed countries and the developing world, the investigation of innovation in agricultural machinery has been much less systematic. Nevertheless, case studies, actual observation, and discussions with engineers and machinery manufacturers reveal very similar trends. For example, the emergence of a diversified machinery industry from small shops is well known for the Indian Punjab. The Thai power tiller industry has been well documented by Wattanutchariya (1981). Innovations in the Philippines have been described by Mikkelsen and Langam (1981).

Generalization 19. *In the early phases of machinery invention, subinvention and adaptation are done almost exclusively by small manufacturers or workshops, working closely with farmers. Public sector research has contributed little to machinery development, but more to education. The contribution of large corporations increases over time, but continues to be largest in the area of engineering operations.*

The reasons for these patterns are threefold:

- In sharp contrast to biological innovation, for which public funding is crucial, private makers of machinery can capture the gains from their innovation by selling machines. The innovator's rights are more protected, the more developed the patent system is and the better it is enforced. (For a full discussion of alternative patent systems, see Evenson 1982.)
- Because many adaptive discoveries are specific to particular regions, farmers, blacksmiths, and small firms have an important advantage over public research institutes or large corporations.
- Unlike biological or chemical inventions, mechanical innovation does not usually depend on the university-acquired skills of chemistry, genetics, or statistics. Mechanically minded individuals with little formal education are thus not at a disadvantage. Metallurgical and mathematical knowledge become more important when the design of complex or self-propelled machines needs to be refined; at this stage, engineering staffs of corporations are more effective.

These characteristics produce the industrial structure that Evenson described for the United States, but which has occurred wherever mechanization proceeded rapidly.

Generalization 20. *At the beginning of a mechanical spurt, many small firms enter with alternative designs. The most successful either grow or are bought up by larger firms; small producers disappear or revert to servicing machinery.*[9]

Evenson also shows evidence for the following:

Generalization 21. *Inventive work on a particular operation often precedes by decades the widespread use of machinery. It reaches a peak during the initial adoption cycle, when derivative invention, refinements, and adaptation to different environments are required.*

The longest lags between inventive activity and adoption of machines occur when inventors are trying to mechanize operations for which there is as yet little demand. Inventive work on seed drills and harvesting in early nineteenth-century Europe provides one of the clearest examples of this lag, but the same phenomenon occurs in many developing countries, especially in the machinery parks of publicly funded programs in agricultural engineering.

Policy Implications for Developing Countries

Developing countries have a wide range of machine processes and basic engineering solutions from which to choose. They thus seldom need to solve basic engineering problems for operations they want to mechanize. Their bigger task is to foster a healthy climate for the reinvention, adaptation, and straightforward copying of existing designs. By the very nature of agriculture, this process must be decentralized and carried out separately for different countries or agroclimatic regions.

In choosing how to mechanize, different countries should expect different results from mechanization. In general, mechanization will contribute little to growth in countries without a land frontier and with densely populated farmland—such as Bangladesh, most of India, and China. Given the fact that a high proportion of the work forces in these countries is still engaged in farming, even very rapid growth in the rest of the economy will not lead to rapid wage increases. Labor scarcity cannot be expected to arise from nonagricultural growth in the near future as a driving force for mechanization. By contrast, labor market pressures are quite different in the middle-income countries of South America, such as Brazil.

Developing countries are also faced with the question of which operations to mechanize next. Local farmers tend to be the best judges. Outsiders often know too little about local farming—or worse, they may try to solve perceived problems with solutions imported from their home environment. The patterns of mechanization discussed in this paper may be helpful in anticipating future developments somewhat better.

As for government intervention, the historical record is quite clear. Mechanization in today's industrial countries did not depend on direct government involvement in machinery development, production, technology choice, or finance.[10] The same is true of the most successful experiences in the developing world, such as the mechanization of milling, pumping, or harvest processing. Once economic conditions have produced effective demand for machinery, private firms have responded rapidly in the developed world. On a smaller scale, responses have been equally rapid in economies as diverse as Thailand and Mexico.

In the developed world, government policy toward mechanization has been confined to patent laws for enforcing innovator's rights and encouraging disclosure; testing of machinery, support of standardization measures, and dissemination of information; and support of agricultural engineering education and some university-based research. These are clearly appropriate interventions. Unlike the case of agricultural research, it is difficult to make a case for any further intervention on the grounds of economic welfare.

Where governments have intervened more, they have either had little success, as in numerous publicly funded research efforts, or they have made wrong or controversial choices.[11] Pakistan not only subsidized big tractors, but also prohibited imports of all but a few brands.[12] Its trade policies restricted imports of many smaller machines and implements and made it almost impossible for small innovating firms to import foreign designs for local adaptation. The contrast between Pakistan and Thailand could hardly be sharper. Thailand's laissez-faire policy has resulted in the development of indigenous power tillers and small tractors, a wider choice of machinery, and few adverse social consequences.

Brazil's approach has been to encourage mechanization by subsidizing loans for buying machinery. Because interest rates were often lower than inflation, real borrowing costs were negative. There is ample evidence that credit subsidies, especially for tractors and other big machines, were obtained mainly by large farms and latifundia. They gained a cost advantage over small farmers and expanded at their expense. This process has been documented for Pakistan in two studies over a fifteen-year period (McInerney and Donaldson 1975; Lockwood 1981)[13] and for Brazil (Sanders and Ruttan 1978). Furthermore, the subsidies often favored the better-off regions: Sanders and Ruttan show that they have increased imbalances between São Paolo province and the poor Northeast. In China, subsidized credit and energy have undoubtedly benefited the richer regions over the poorer ones, where investment in machines is still very limited.

Generalization 22. *Subsidies to mechanization tend to have little effect on output, while damaging employment. They also tend to favor larger farms and richer regions.*

By contrast, where mechanization has occurred spontaneously in response to rising demand for labor in the rest of the economy, the social consequences have rarely been harmful. Released workers have been redeployed in jobs where they were more productive and received higher wages, and others have ended up farming larger areas.[14] Even when mechanization is spontaneous, however, governments may sometimes be faced with severe distributional dilemmas. For example, it appears that combine harvesters would be modestly profitable in the Indian Punjab, but their introduction would displace many migrant workers from the poorest regions (Laxminarayan and others 1981). In the absence of rapid employment growth elsewhere, the Indian government may be justified in banning combines. Mechanical rice milling has been controversial in Indonesia (Timmer 1974, Collier 1974) and is now penetrating Bangladesh. It reduces the demand for women workers, who—because of social customs—have few employment options. On efficiency grounds, milling machines are clearly warranted; on equity grounds, their effects may be harmful.

Implications for China

Any analysis of the potential contribution of mechanization to growth applies as much to a socialist as to a capitalist economy. In both, payoffs depend on the opportunity costs of labor, land, and capital. Despite numerous policies and programs to influence mechanization in China over the past thirty years, the results are surprisingly similar to those of other labor-abundant developing countries: a limited spread of tractors, which are used for tillage and transport, plus substantial mechanization of power-intensive operations such as harvest processing and pumping. Since China has abundant labor but a shortage of land, the policy implications for mechanization do not differ much from those for similarly endowed economies.

Equity issues, however, may differ a little in China. In principle, when a brigade or production team invests in a machine, all its members save on the work and share in the returns from agricultural production. They should therefore be able to mitigate the potential for distributional inequities within the commune and judge mechanization primarily in terms of profit. This might help to explain the complementarity between animal and mechanical power in Chinese agriculture found by Ramaswamy (1981).

Interregional equity is more complicated. As long as migration is restricted in China, labor cannot be redeployed from slow-growing to fast-growing regions. The fast-growing regions may therefore experience increased demand for labor and find it necessary and profitable to mechanize. The alternative—allowing migration to solve regional labor scarcities—may be better than mechanization. Migrants from poorer regions could share the faster growth of the richer ones, and scarce capital could be used for investments other than machines. Current Chinese policy emphasizes "sideline activities," the redistribution of industrial and service activity to rural areas to overcome interregional problems of income distribution. Although such decentralization is certainly desirable and necessary, locational and natural disadvantages in many regions limit how much can be achieved.

Abstract

The article provides a detailed comparative historical review of the patterns of agricultural mechanization by operation. The first section reemphasizes the major conclusions of the induced innovation literature, and the second section shows the remarkable similarity in the early mechanization experiences of the developed and developing countries. New mechanical power sources were first used on power-intensive operations such as processing, pumping, transport, and tillage, while mechanization of control-intensive operations came much later and usually in association with high wages. Finally, an investigation of the process of agricultural machinery innovation shows that the public sector and corporate research has contributed little to machinery invention. Machinery innovation has generally been the domain of small manufacturers, with corporations becoming significant in later stages of product development and engineering optimization.

Notes

1. Induced innovation processes can also be documented in the developing world. Mechanization in central Thailand, one of the most successful cases (discussed in detail in World Bank 1983), appears to have been clearly induced by increasing scarcity of labor.

2. For evidence that tractors have no direct effect on yield in South Asia, see Binswanger (1978).

3. Final demand is said to be elastic or inelastic according to whether an increase in quantity supplied leads to a small drop (elastic) or a large drop (inelastic) in the price received.

4. For a discussion and estimates of temporary migration for harvest work, see Laxminarayan and others (1981).

5. For a thorough discussion of this issue, see Binswanger and Rosenzweig (1982). That discussion distinguishes carefully between the effects of operational holding size and ownership holding size on costs of capital and labor. Here we assume that the operational and ownership holdings are closely related.

6. For careful investigation of the impact of scale on machinery adoption in nineteenth-century United States and Britain, see David (1975).

7. This is so despite the well-publicized growth of tractor sizes and harvesting machines in the United States. That growth occurred in response to the growth in farm size and in the number of tasks performed by tractors; it was an indirect response to the unprecedented wage increases of the past forty years.

8. For the data on which this section is based, see Binswanger (1984).

9. Switzerland, for example, had at least five producers of tractors in 1950, none of which survived.

10. Not included here are general policies, such as agricultural price policy, which have side effects on mechanization but affect all agricultural investments.

11. A good case in the developed world is the invention of the tomato harvester in California. For a recent summary of the controversy, see de Janvry, LeVeen, and Runstein (1980).

12. The brand choices had usually been made under donor pressure rather than as conscious economic choices. Brands from different countries were added whenever govern-

ments donated or helped finance tractors. Several were later dropped when aid stopped (Lockwood 1981).

13. In Pakistan many farms grew very rapidly as a result of tenant eviction, purchases, additional renting of land, and a modest amount of reclamation.

14. It must be recognized, however, that wages might have risen even faster in the absence of mechanization.

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