Part I. A History and Analysis of Agricultural Productivity Gains in the U.S., 1950-95

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Executive Summary

- Productivity gains in American agriculture began early in the century, accelerated between the World Wars, and achieved take off from 1950-96. Yet today, many question whether the high inputs that have made such yields possible are sustainable, and whether the throughput of the agricultural system might be reduced. One such possibility, explored in detail in Part II of the larger study, is whether genetically engineered soybeans, corn and cotton can substitute new crop characteristics based on genetic information for a variety of energy-intensive inputs.

- In this Part I of the study, we examine the historical evolution of agricultural technology. Specifically, we discuss overall trends in factors of production (inputs) that have driven yields: land, labor and technology; institutional changes in the Land Grant Universities and private sector; fertilizer, pesticides, fuel and genetic improvements. This is followed by crop-specific analysis of corn, soybeans and cotton. The study concludes with a discussion of tillage systems and "precision agriculture," both of which are taken up in greater detail in Part II of the larger study.

- In the long view, agricultural productivity growth in the U.S. has depended on large areas of fertile, well-watered cropland and increasing levels of mechanized inputs, together with high levels of "human capital" (know-how) resulting from a comparatively well-educated agricultural labor force. By 1920, agriculture had been joined to the energy sector by the internal combustion engine, as well as to the emerging fertilizer industry.

- Nitrogen, phosphorus and potash fertilizer industries grew up alongside production agriculture between the World Wars and especially after World War II, when ammonium nitrate used in munitions and ammonia by-products of the natural gas industry were exploited to power a nitrogen fertilizer complex. This was joined by rock deposits of phosphate in the South and West, and by potash from potassium chloride deposits in Canada and elsewhere.

- Beginning in the 1950s and 1960s, the pesticide industry also emerged as a key input to crop production. Between 1964 and 1982, total pesticides (herbicides, insecticides and fungicides) applied to corn (active ingredient) increased from 41 to 273 million pounds, then fell off to its 1995 level of 201 million pounds. Soybeans received 9 million pounds of pesticides in 1964, rising to 145 million pounds in 1982 and declining to 68 million pounds in 1995. Cotton received 95 million pounds in 1964, rising to 111 million pounds in 1971, falling to 41 million pounds in 1987 and rising again to 83 million pounds in 1995.

- Fuel used on farms displayed increasing substitution of diesel for gasoline. From a high of 4.5 billion gallons of gasoline in 1975, farm consumption fell to 1.4 billion gallons in 1995. Liquid propane gas also fell, from 1.4 billion gallons in 1974 to 0.8 billion gallons in 1995. Diesel fuel use, meanwhile, increased from 2.5 billion gallons in 1989 to 3.6 billion gallons in 1995. Irrigated acreage also increased, most notably on corn.

- A final component of yield increases in U.S. agriculture as a whole was seed and the genetic information it contains. While much of the attention focuses on hybrid corn, plant breeding also accounted for major genetic gains. Soybeans and cotton also experienced genetic improvement. The latest chapter in these improvements is biotechnology, and the fixing of plant characteristics such as herbicide and insect resistance.

- One of the most difficult questions surrounding the future of all of the above inputs concerns substitution possibilities. It is clear that mechanical, biological and chemical inputs have substituted in major ways for labor, and that genetic information has complemented this process in the form of advanced seeds and hybrids. It is easy to overstate the importance of various inputs including fertilizer and pesticides, if substitution possibilities are underestimated. Reductions in these inputs due to biotechnology, and the complementarity of biotechnology with tillage practices and more precise input applications, all emphasize that agriculture is a system, and that systemic interactions and major substitution possibilities are critical to evaluating its future.

Corn

- Corn production trends indicate overall increases in yields with some decreases in the rate of increase since 1975, together with increasing variation from year to year. From 1951 to the record in 1994, yields rose from an average of 37 to 139 bushels per acre. Decomposing the sources of these increases suggests the importance of hybrid varieties and other genetic gains, herbicides, fertilizer and plant densities, in addition to earlier planting dates and improved cultural practices. Yields have been held back by corn following corn and resulting pests and interference, as well as soil erosion. Planted corn acres have varied from a high of about 85 million acres in the 1970s to a low of 60 million acres in 1983, affected by both weather and government acreage retirement programs.

- Corn is heavily fertilized, especially with nitrogen. Application rates of nitrogen and potash rose from levels of 60 and 40 pounds per acre, respectively, in 1964, to about 130 and 80 pounds in the 1990s.

- Pesticide use rates on corn (active ingredient) have moved upward dramatically. Herbicide use rose from 25 million pounds in 1964 to a high of 243 million pounds in 1982 and fell to 186 million pounds in 1995. Per acre applications tripled from 1964 to 1980 then leveled off, declining in the 1990s. Specific herbicides changed, and their efficacy increased, resulting in better weed control with fewer pounds of active ingredients. Insecticides on corn are applied mainly to control corn rootworms. Use rose from about 16 million pounds in 1964 to 36 million pounds in 1980, declining to 14 million pounds in 1995. Application timing and methods can greatly affect total pesticide use on corn.

- Fuel and energy inputs to corn production are lower than estimated in the early 1970s, and show that nitrogen fertilizer and pesticides are more important indirect sources of energy inputs than direct fuel use.

- Per acre input expenditures (in constant 1992 dollars) on corn show that fertilizer costs have declined somewhat since the mid-1980s, and chemical costs have trended upward since the mid-1970s. Energy costs (as distinct from energy inputs) have risen in constant 1992 dollars from 11.86 dollars per acre in 1986 to 20.36 dollars per acre in 1995. These trends suggest incentives to economize on the use of farm chemicals and energy while maintaining current levels of fertilizer use per acre.

Soybeans

- Soybean production trends show yield increases of about one-third of a bushel per year for the last 41 years, with a slight increase in trend since 1975, and increases in variation from year to year. In 1955, planted acres stood at 20 million, rising to a high of about 71 million acres in 1979 and to 1996 levels of about 65 million acres.

- Soybeans are nitrogen-fixing, so that applications of nitrogen are relatively low. Total fertilizer applications have risen mainly as a function of acreage. On a per acre basis, application rate increases were from about 14 to about 28 pounds for nitrogen between 1964 and 1995, from about 37 to about 84 pounds for potash, and from 30 to 54 pounds for phosphates.

- Pesticides used on soybeans are mainly herbicides. In 1995, soybean crops received 69 million pounds (active ingredient) of pesticides, nearly all of which was herbicides. Herbicide types have evolved rapidly, many substituting for alachlor, and have required fewer active ingredients per acre.

- Fuel and machinery use on soybeans is largely coincident with that used on corn, and is difficult to evaluate separately.

- Per acre input expenditures on soybeans (in constant 1992 dollars) show important increases in chemical costs, which have risen from 13.79 dollars in 1985 to 21.58 dollars in 1995. Energy costs have fallen from 12.49 dollars in 1985 to 8.68 dollars in 1995. These figures suggest strong incentives to economize on the use of herbicides on soybeans, and the appeal of farming systems which reduce applications.

Cotton

- Cotton yields remained relatively flat from 1960 to 1980, but moved upward in the 1980s, reaching a record 708 pounds per acre in 1994, compared with 446 pounds in 1960. Trends indicate a rising rate of yield increase in the period 1975-95. Cotton acreage has rebounded since 1989, averaging 13.3 million acres since 1990, with growth especially in the Southeast. Planted acres have been very uneven, and production as well, reflecting shifting cultivation and differences in irrigated and dryland yields.

- Fertilizer is heavily used on most cotton acres, especially nitrogen, although nitrogen application rates stayed in the range of 80 pounds in the 1990s, jumping to 110 pounds in 1994 and falling back to 95 pounds in 1995. Total nitrogen use has risen with renewed cotton planting in the 1990s. Potash and phosphate are used on 40 and 50 percent of fields respectively; in 1995, application rates were from 40-50 pounds per acre for both inputs.

- Pesticide use on cotton is heavy, especially considering the much smaller planted acreage devoted to cotton (16 million acres in 1995) compared with corn (71 million acres in 1995) and soybeans (62 million acres in 1995). Cotton growers used 84 million pounds of pesticides (active ingredient) in 1995, compared with 69 million pounds applied to soybeans and 202 million pounds applied to corn. Even so, total use has fallen from a high point in 1971, although expenditures per acre on chemicals for cotton are the highest of all major field crops.

- Data on direct fuel and energy use on cotton are scarce, although high levels of nitrogen and pesticides make its indirect energy use per acre relatively high.

- Per acre input expenditures (in constant 1992 dollars) for cotton indicate falling chemical costs since the 1980s, while fertilizer costs have risen, with energy variable and seed costs moving upward from a low of 6.70 dollars per acre in 1986 to 14.25 dollars per acre in 1995.

Tillage practices and Precision Farming Methods

- Conservation tillage, including no-till, ridge till and mulch till, is an overall approach to crop residue management to protect the soil surface from wind and water erosion and to help maintain soil structure. Conservation tillage systems have been adopted largely because they are cost-effective, reducing fuel and machinery needs while maintaining and sometimes improving yields, depending on soil types and drainage. Adoption has been highest in corn-soybean rotations, but quite low on cotton acres. Some increased herbicide use is generally needed, creating potential synergies between herbicide resistent crops such as Round-up Ready soybeans and such tillage methods.

- Precision farming methods include the increased use of soil testing and mapping with applications of chemicals, planting and cultivation geared to variations in soils and landscapes. While the number of issues (and unknowns) involved in precision agriculture is quite large, these methods also appear complementary to emerging seed varieties such as Round-up Ready soybeans, Bt corn and cotton.

Part I. A History and Analysis of Agricultural Productivity Gains in the U.S., 1950-95

Introduction

American agricultural productivity represents one of the great technological breakthroughs of the modern age. Beginning early in the century, accelerating between the World Wars, and achieving take-off in the post-war period, productivity gains on American farms demonstrated the capacity of individual initiative, applied science and technology to boost output per acre and per man-hour. Yet today, questions remain whether these productivity increases are environmentally sustainable -- whether the fertilizers, pesticides, machinery and hydrocarbon fuels driving the system can continue to be used without compromising the quality of the land, water, air and health of current and future generations. In the face of these concerns, Monsanto has undertaken research and marketing efforts to reduce the "throughput" of the agricultural system by substituting biotechnology in the form of new seed varieties for other, less sustainable inputs. These varieties include Bt corn, Round-up Ready soybeans and Bt cotton. Bt corn and cotton are named for ***Bacillus thuringiensis***, a soil bacterium that produces endotoxins with a specific insecticidal activity. When genes from this bacterium are transferred to corn and cotton, they confer resistance to the European corn borer and the cotton budworm and bollworm. Round-up Ready soybeans are genetically engineered to that they are resistent to the amino acid starvation and cellular death that results from the broad spectrum herbicide, glyphosate, the trade name of which is Round-up. All three crops hold the promise of substituting genetic information in plants for a variety of energy-intensive inputs.

The purpose of this study is to place this genetic engineering research and marketing in the context of the historical evolution of agricultural technology generally, to examine the on-farm savings in energy-intensive inputs that may result, and to consider the global opportunities to transform high input agriculture into a more sustainable enterprise. Part I, presented in the pages to follow, provides the historical context of productivity gains in U.S. agriculture for corn, soybeans and cotton, with particular attention to fertilizer, pesticide and fuel use. These and other factors of production define what has come to be known as "high input" agriculture.

High input agriculture has been an extraordinary success story from a productivity point of view. Between 1948 and 1993, U.S. agricultural productivity measured as output per unit of input increased at an average annual rate of 1.8 percent. It was the principal factor responsible for economic growth in the agricultural sector, well-exceeding the average annual rate of productivity growth in the non-farm sector of 1.1 percent (Figure 1). Basically, farmers substituted mechanical technology and inputs including pesticides, fertilizer, energy and improved seed for labor on a relatively fixed area of land. Labor costs fell from 41 percent of total farm inputs in 1948 to 24 percent in 1993. Capital (mainly farm equipment) costs increased from 9 percent of the total to 28 percent over the same period. Other purchased inputs costs increased at an average rate of 1.3 percent a year, although pesticide use grew by 6.1 percent, while feed, seed and livestock grew by 2.2 percent and fertilizer and energy grew by 1.7 and less than 1 percent respectively (USDA, ERS, AREI, July 1996).

Figure 1. Productivity Growth in U.S. Agriculture, 1948-93.

Source: USDA, ERS, *AREI Updates*, July 1996, p. 1.

The reasons for these productivity increases run deeper than these statistics and have their origins in technological and institutional changes beginning in the mid-19th century. First, the settlement and conversion to agricultural use of the North American continent between 1820 and 1920 created a huge area available for cultivation and pasturage, amounting to almost 400 million acres in the U.S. alone. Much of this area, especially the roughly 200 million acres in the Corn Belt and Delta states forming the North and South reaches of the Mississippi drainage basin, are well-watered, fertile soils ideally suited to crop production. The fact that the Mississippi forms a North/South axis of production (and transport) is also significant, since it allows for variations in both temperature and moisture to be absorbed from year to year (in contrast to the largely East-West axis of European, Russian and Asian areas of cultivation, where yearly variation in yields are much more pronounced). In addition, this orientation allows planting and harvesting to proceed from South to North, often with large mechanical planters and harvesters that move from Texas north toward the Canadian border with the seasons.

In addition to these natural advantages, American agricultural productivity is supported by an educational and research infrastructure in its land grant colleges and the private sector that make American farmers some of the most technologically sophisticated in the world. Unlike many other countries, where farmers are relegated to the status of peasants, U.S. producers have received and continue to receive advanced training and support from the education and research establishment, investments in "human capital" that have paid handsome rewards to society as a whole.

Third, American agriculture is supported by industries producing fertilizers, pesticides, farm machinery and seeds ideally suited to increasing output per acre while minimizing labor inputs. These biological, chemical and mechanical inputs have substituted for on-farm hours of labor so as to allow maximum yields while substantially reducing labor requirements. It is also true that the expanded use of these inputs has created environmental stresses and damages, including soil erosion and surface and groundwater pollution. These environmental damages will play a key role in the analysis to follow.

A final element explaining American agricultural productivity growth, and a main focus of the larger study of which this report is a part, is success in developing seeds and the genetic material they contain. Raising yields over time has been the result of highly successful programs of plant-breeding that have modified plant characteristics to increase their capacity to use nutrients, water and other inputs in the most efficient ways. Apart from plant breeding (including hybridization, mainly in corn), the main purpose of the larger study will be to investigate the latest chapter in the optimization of plant genetic information: agricultural biotechnology. In addition to raising yields, the promise of modern biological technology may be to substitute for the use of other inputs, including those that can pose particular risks to the environment. In Part II of the study we shall examine how Round-up Ready (RR) soybeans, Bt corn and Bt cotton can affect the total use of fertilizers, pesticides, fuel, and machinery not only to reduce farm-level costs, but also to improve tillage systems in ways that mitigate some of the negative effects that modern agricultural production has on environmental quality.

Part I of the study provides an historical overview of productivity gains in American agriculture, considering broad trends in the uses of land, labor, fertilizers, pesticides, fuel, machinery, and seeds. These factors of production are then linked to yield increases in the three crops of interest: corn, soybeans and cotton. After specific consideration of each of these crops, focusing especially on pesticide, fertilizer and fuel use, we consider recent developments in tillage practices and the increasing precision with which agricultural inputs are applied at the farm level. Part II of the study, now in the process of completion, will provide detailed regional assessments of farm-level use of pesticides, fertilizer and fuel on soybeans, corn and cotton with and without the genetically-engineered seed varieties, and under various cropping conditions, as well as detailed assessments of certain environmental impacts of these technologies. Part III will focus on global production and resource use, and the possible use and impact of these technologies in other parts of the world.

A. Factors of Production: A Long View

1. ***Land, Labor and Technology***

The factors underlying U.S. agricultural production are land and its use, labor and human capital, fuel and machinery, fertilizer and pesticide inputs, and seed and genetic information. Throughout American agricultural history, the land and its use has been a basic determinant of productivity. Unlike most of the civilized world, until the last century the majority of the land resource of North America had never been cultivated. While soil productivity and available moisture in the U.S. vary dramatically, and both decline markedly in the arid West, the U.S. is endowed with some of the most fertile agricultural land in the world. With the exception of California's Central Valley, most of the highest productivity land in the U.S. lies in the huge Mississippi Basin, including the main tributaries of the Ohio, Missouri, Illinois, Arkansas, Minnesota and Wisconsin Rivers. In the Northern reaches of this production area, known as the Corn Belt, alluvial soils were deposited by a succession of glaciers, then covered by grasslands and forests which laid down season after season of organic matter over tens of thousands of years. As a result, in parts of Illinois at the epicenter of the Corn Belt, topsoils remain as much as 10 feet deep. In the lower Mississippi Basin, large floodplains left soils suited to a variety of crops, including cotton, among the most demanding of soil nutrients of any major crop.

In 19th and early 20th century agriculture, these soils were the primary explanation for U.S. agricultural productivity, and were tilled, planted, and harvested largely by hand. Beginning in the mid 19th century, the demands for U.S. agricultural output began to rapidly outpace the supply of labor available to meet it, especially given the abundance and

Table 1. Farm Machinery: Number of Specified Kinds on Farms, and Tractor Horsepower, United States, Selected Years, 1910-88.[a]

Source: Cochrane, 1993, p. 198.

productivity of the land. Two primary sets of responses to this disequilibrium resulted: one technological, the other institutional (Hayami and Ruttan, 1985).

In the 1840s and 50s, American grains began to supply the deficit production areas of war-ravaged Europe, creating premiums for the development of land-using, labor-saving mechanical technologies. Among the most famous were the development in 1837 of John Deere's first plows, followed in 1850s by Cyrus McCormick's reaper and a variety of grain combines. By the mid-1850s the John Deere Company was manufacturing over 10,000 plows a year. The McCormick reaper represented the most significant labor-saving mechanical technology in grain harvesting in several millennia. Since 1000 B.C., the hand scythe and cradle had been used to harvest grain. The mechanical reaper used the rotation of the wheels to turn a sickle bar which cut grain onto a platform from which it was raked by hand. Later innovations combined threshing and winnowing, separating straw from the grain and seed and eliminating the chaff. These came into wide use in the 1870s and 1880s, and as many as 40 horses pulled huge combines weighing 15 tons that could cut swaths of grain up to 35 feet wide. In addition to these combines, other implements were innovated that markedly improved the ability of a few men and women to plant, till and harvest large acreages: harrows, disks, grain drills, mowers and hay making equipment. All of these innovations were given further impetus by the labor shortages of the American Civil War and the period of European unrest in the latter 19^{th} century, which raised grain export demand.

At the turn of the century, steam engines were mounted on the great combines, and gasoline-powered tractors were developed, linking farm mechanization inexorably to petroleum fuel consumption. In 1910, 1,000 tractors were in use in the United States. Five

Table 2. Public Expenditures in Millions of Dollars for Research and Extension in Agriculture, Selected Years, 1920-90.

Source: Cochrane, 1993, p. 247.

years later, 25,000 tractors were in use, and by 1920, 246,000 tractors were in use, a ten-fold increase in each five-year interval. Tractor numbers peaked in the mid-1960s, but have remained in the range of 4.7 million since then, while tractor horsepower has increased from 176 million in 1965 to 309 million in the early 1980s (Cochrane, 1993, p. 197). Table 1 shows farm machinery data for 1910-1988, the last year in which they were collected.

2. ***Institutional Innovations***

At roughly the same time as these mechanical innovations took hold, a set of institutional innovations emerged that would lay the foundation for increases in the labor productivity of U.S. agriculture: investments in "human capital" at the Land Grant Universities by the federal government. In the mid-19th century scientific and technical schools were founded, including the Agricultural College of Michigan in 1855, the Yale Scientific School in 1847, the Pennsylvania State College in 1854, and the agricultural unit of the University of Wisconsin. During the same period Congressman Justin Morrill of Vermont began a campaign in favor of federal support for such institutions, an effort fought by southern congressional leaders opposed to federal funding for education and vetoed by President Buchanan in 1859. After secession Morrill proposed and Congress passed the Morrill Act of 1862, endowing and supporting through land grants (30,000 acres per member of Congress) at least one college in each state dedicated to agricultural and technical education. A month earlier, President Lincoln established the U.S. Department of Agriculture. Some states, such as Wisconsin and Minnesota, merged the function of the Land Grant College with the state university; others, such as Texas and North Carolina, established separate agricultural and mechanical (A&M) colleges, and some separate A&M institutions for blacks, leading to a dissipation of effort.

In 1887 the Hatch Act, providing funds from the sale of public lands, offered further support for agricultural experiment stations, especially research into the organic chemistry of soils and plant nutrients, plant genetics, animal health and nutrition, and applied economics. The final component in this mix of human capital formation came with passage of the Smith-Lever Cooperative Extension Act of 1914, in which federal funds matched state appropriations for adult education. Estimates of the internal rate of return to these public investments in the post-war period average about 40 percent -- high by any standards (Table 2).

As noted above, the mechanical technologies of the late 19th century had all been driven by animal draft, but by 1920 the internal combustion engine begun dramatically to displace animal power, making agriculture a major consumer of petrochemical fuels. Apart from direct on-farm fuel use, petrochemicals were also linked in critical ways to the fertilizer industry. This industry can be subdivided into the three main fertilizer ingredients: nitrogen, phosphorus and potash.

3. ***Fertilizer***

The first use of synthetic nitrogen fertilizer in the United States was in 1926, resulting in part from the conversion after World War I of production of ammonium nitrate, the main explosive agent in many bombs and shells. (The explosive properties of ammonium nitrate were first recognized in Sweden in the 1880s, where Alfred Nobel was issued a patent on it as a replacement for nitroglycerin in 1879.) In order to reduce its explosive tendencies, it was mixed with limestone, gypsum, chalk or ammonium sulfate for fertilizer. After World War II, production at the large Muscle Shoals, Alabama munitions factory was converted to fertilizer by the Tennessee Valley Authority (TVA), together with a Hercules Powder Company plant in

California and three Canadian plants (Nelson, 1990, p. 359). Production of solution and solid ammonium nitrate for fertilizer increased from 383,000 tons in 1943 to 6.4 million tons in 1974.

In addition to ammonium nitrate, nitrogen fertilizer (N) is also applied as anhydrous ammonia, as a nitrogen solution, as urea and in various mixtures. Anhydrous ammonia contains the highest nutrient content of any fertilizer, allowing it to be shipped long distances at low cost, and can be injected directly into soil or mixed into irrigation water. It is, however, a potentially hazardous gas at normal pressure and temperature and must be handled with care and kept pressurized. Its application in irrigation water was pioneered in the citrus groves of California in the 1930s by the California Citrus Growers Association Laboratory and the Shell Chemical Company. A second category of nitrogen is a nitrogen solution, in which liquid ammonia or soluble nitrogen dissolved in water is applied directly to the soil. The use of ammonia as fertilizer established the historical link from agriculture to the gas industry, of which ammoniacal liquor is a byproduct. As early as 1843, ammonia
from illuminating gas works in England and Scotland were applied to wheat, and experimentation continued for the next century. In the 1920s, experiments combining ammonia with phosphates so as to optimize the combination led to patents granted to the forerunner of Allied Chemical (the Barrett Company) and Dupont. The first tankcar solution was shipped by Allied Chemical in 1949. In the 1960s, a third category of nitrogen solution material, urea-ammonium nitrate (UAN), emerged with different levels of N concentration suited to different climates. UAN contains more N than any other liquid solution, is easy to apply, mixes well with water, and can be transported in pipelines, barges or railroad cars. A final category of nitrogen fertilizers involves mixtures of urea with other materials such as formaldehyde or sulphur that cause the N

to be released more slowly, corresponding to the needs of the growing crop. First marketed in the 1950s, slow release formulations remain expensive and are generally restricted to high-value vegetables, lawn turf and ornamental shrubs (Nelson, 1990, p. 371). Table 3 shows nitrogen and other nutrient on various crops in 1995.

After nitrogen, the second largest ingredient in fertilizer is phosphatic material. Phosphate fertilizers (P_2O_5) are largely mined from natural rock deposits. Phosphate rock deposits were first mined in Europe in the mid 19th Century. The result of sedimentary deposits of ancient ocean life, the mined rock is washed, dried and designated in terms of its "bone phosphate of lime" (BPL) phosphate content, an inheritance of use of pulverized bone meal as a soil supplement (Nelson, 1990, p. 56). Late in the 19th Century, large deposits were discovered in North Florida, near Gainesville, and central Florida, near Ft. Meade. In the early 20th Century, discoveries in Tennessee began to be exploited, and smaller companies began to be acquired, notably by Chicago meatpacking firms such as Armour and Swift, which had parallel interests in bone meal. In the 1950s, concentrated superphosphate began to be replaced by triple superphosphate and in the 1960s by ammonium phosphates. In contemporary phosphate plants, phosphate rock is pulverized and mixed with sulfuric acid and phosphoric acid to produce a slurry. Gypsum crystals are removed (and constitute a significant waste stream). The remaining phosphate material is then mixed with anhydrous ammonia to produce granular and nongranular forms of ammonium phosphate, available as monoammonium phosphate (MAP) and diammonium phosphate (DAP). Table 3 shows phosphate use on crops in 1995.

Table 3. Commercial Fertilizer Application Rates by How Applied, Major Crops and Producing States, 1995.

Application method	Corn	Cotton	Fall potatoes	Soybeans			Durum wheat	Spring wheat	Winter wheat	All wheat
				North	South	Both				
	Pounds per treated acre									
Nitrogen:										
Broadcast (ground)	85	55	125	22	37	26	64	58	56	56
Broadcast (air)	100	43	81	64	NR	64	26	79	29	36
Chemigation	72	84	146	2	NR	2	33	35	97	83
Banded	26	76	85	13	14	13	11	17	18	17
Foliar	NR	45	5	NR	NR	NR	NR	NR	NR	NR
Injected (knifed in)	125	101	112	97	57	93	67	69	60	63
Phosphate:										
Broadcast (ground)	64	41	139	59	51	57	28	35	44	42
Broadcast (air)	61	40	98	44	45	44	20	42	25	30
Chemigation	31	41	115	NR	NR	NR	NR	NR	2	2
Banded	40	41	114	35	33	35	24	26	27	26
Foliar	NR	14	6	NR	NR	NR	NR	NR	NR	NR
Injected (knifed in)	37	52	138	71	37	65	24	24	24	24

Potash:										
Broadcast (ground)	92	61	156	97	68	89	50	27	59	52
Broadcast (air)	106	30	83	96	60	86	NR	NR	7	7
Chemigation	62	11	87	@	NR	@	NR	NR	NR	NR
Banded	38	29	116	38	76	42	12	14	20	15
Foliar	NR	3	3	NR	NR	NR	NR	NR	NR	NR
Injected (knifed in)	42	27	65	NR	NR	NR	NR	22	7	12

@ = Less than 0.5 pound.
NR = None reported.
Source: USDA. ERS. National Resources and Environment Division. "1995 Nutrient Use and Practices on Major Field Crops." *AREI Updates*. Number 2; May 1996. p. 4.

Figure 2. U.S. Fertilizer Use 1964-95.

Source: USDA. ERS. National Resources and Environment Division. "1995 Nutrient Use and Practices on Major Field Crops." *AREI Updates*. Number 2; May 1996, p. 1.

The third main fertilizer ingredient is potash. The first patent issued in the United States (signed by George Washington) was a process to extract potash (K_2O) from wood ashes. Wood ashes were regularly worked into fields after clearing and burning of stumps and slash, or were brought to a central "potash house" for leaching and drying. In the mid 19th century, over 600 plants produced potash from wood ashes, much of which was exported (Nelson, 1990, p. 44). In the early 20th century, with growing agricultural demand, potash was largely imported from Germany, with a small domestic production drawn from potassium chloride deposits in salt lakes. In the face of critical shortages in World War I, potash was extracted from ocean kelp, from the brines of Searles Lake, California, the Great Salt Lake in Utah, and from alkali lakes in Western Nebraska and deep wells in the Permian basin of Texas. Potash was also extracted from molasses distillery waste, beet sugar waste, and the traditional source: wood ashes. In 1925, a large deposit of potassium salts was found during wildcat oil drilling near Carlsbad, New Mexico. In 1938, these deposits and brine operations at Searles Lake and Bonneville Flats, Utah led domestic supplies to exceed imports for the first time. By 1962, a huge potassium chloride deposit was under full exploitation in Saskatchewan, which could be mined at much lower cost than in the U.S., and which was linked by rail to the Midwest Corn Belt, which claimed an increasing proportion of use. Canada emerged by the mid 1970s as the major global supplier, providing roughly 95 percent of U.S. imports (Nelson, 1990). Table 3 shows potash use on crops in 1995.

These three fertilizer ingredients: nitrogen, phosphates and potash, are heavily used to help boost crop yields. Nitrogen use, in particular, has grown dramatically in the past three decades. Figure 2 shows overall U.S. fertilizer use from 1964-1995. Of all major crops, corn accounts for the heaviest use and largest aggregate amounts of fertilizer consumed of any crop. The heaviest use of nitrogen fertilizers by state was in Texas, California, Iowa, Illinois, Nebraska, Kansas, Minnesota, Indiana, and Missouri (USDA, AREI, 1995, p. 2). The use of these fertilizers by farmers has grown dramatically, and is closely related to maintaining production at or near current levels.

4. ***Pesticides***

We turn now from fertilizers to pesticides. Generally speaking, the term pesticides covers herbicides, insecticides and fungicides. Commercial use of pesticides in the United States emerged from the biochemical advances of the 1930s and post-war period. Some of the same companies involved in commercial production of fertilizers (e.g., Dupont) were also heavily invested in the development of pesticides. In the early 1990s, the U.S. Environmental Protection Agency (EPA) estimated that roughly 650 different active ingredients were for sale as pesticides, down from 1,400 in earlier years due to the withdrawal of hazardous products and/or obsolescence. New materials, roughly 15 or 20, are added in the U.S. each year. Many inert ingredients are added to pesticides, as well as synergistic materials that enhance their toxicity. An example of a synergist is methylenedioxyphenyl (MDP), which has this property. Most testing of pesticides for toxicity is by active ingredient, rather than by the combinations of inert, synergistic and pesticide materials found together in a single product (Briggs, et al., 1992, p. 3-4).

The use and application of pesticides depends on many factors, including cropping patterns, weather and climate. Table 4 shows 1995 cropping patterns used on land in corn in 17 major growing states, indicating the prevalence of corn/soybean rotations (47 percent) and alternation of corn with other row crops. The timing and application levels of pesticides also vary. Data on pesticide (as well as fertilizer) applications for corn are summarized in Table 5, which shows that about half of all herbicides are applied before or at planting and about half afterward. Almost 80 percent of these are applied at ground level by broadcasting pellets or liquids on the soil or plant. Insecticides on corn are mainly applied at planting, and about half are banded alongside rows and another quarter applied in-furrow (USDA, ERS, AREI, 1996).

On a per crop basis, there is little question that cotton is a major user of pesticides, especially insecticides. Table 6 shows U.S. pesticide use on all corn, soybeans and cotton for the period 1964-1995. Technological changes in the pesticide industry have been dramatic, but most of the technology involved is closely and privately held, making analysis of these changes difficult. Many of the newer products are markedly less toxic than banned products such as DDT. Even so, total use has increased dramatically since the period when Rachel Carson sounded her first warnings over the potential risks of pesticide use.

Table 4. Cropping Patterns Used on Land in Corn, 17 Major Growing States, 1995

Cropping Patterns[1]	DE	GA	IL	IN	IA	KS	KY	MI	MN	MO	NE	NC	OH	PA	SD	TX	WI	Total 17 States
									Million acres planted									
	0.15	0.40	10.20	5.40	11.70	2.15	1.28	2.45	6.70	1.65	8.00	0.80	3.30	1.38	2.80	2.10	3.65	65.10
									Percent of acres									
Continuous corn	33	31	14	10	17	51	16	27	9	18	51	14	13	34	8	26	21	21
Rotation with:																		
Soybeans[2]	33	7	64	63	67	16	56	20	64	41	28	54	33	16	36	1	17	47
Other row crops[3]	30	46	13	20	13	10	18	26	12	29	12	17	23	5	8	54	11	16
Row crops & small grains	1	2	1	1	*	nr	2	nr	5	nr	1	2	nr	2	38	nr	2	3
Idle or fallow	3	14	3	5	1	22	6	24	1	8	7	11	25	11	8	17	6	7
Hay, pasture, other	nr	nr	1	1	*	nr	2	1	1	3	nr	nr	4	4	nr	nr	24	2
All other patterns[4]	0	0	4	0	1	1	0	2	8	1	1	2	2	28	2	2	12	4

nr = not reported.
* = Less than 1.
[1]Based on crops planted in spring/summer 1993 through spring/summer 1995.
[2]Alternating corn and soybeans.
[3]All other continuous row crop rotations except alternating corn and soybeans, e.g., soybeans-corn-corn.
[4]Specific rotation data not available.

Source: USDA. ERS. National Resources and Environment Division. "Cropping Patterns of Major Field Crops and Associated Chemical Use." *AREI Updates*. Number 18; December 1996, p. 2.

Table 5. Chemical Input Practices on Corn for Grain, Major Producing States, 1993.

Practice[1]	IL	IN	IA	MI	MN	MO	NE	OH	SD	WI	TOTAL
Planted acres (million)[2]	10.5	5.55	12.0	2.50	6.30	2.20	8.00	3.50	3.35	3.40	57.30
	---------- Percent of acre-treatments ----------										
Fertilizer: timing											
Fall before planting	30.5	15.8	17.7	9.7	17.0	16.7	8.5	12.9	22.3	8.6	17.9
Spring before planting	49.9	34.8	53.4	23.3	46.7	52.3	24.2	28.9	34.7	23.7	40.1
At planting	6.3	32.0	14.7	43.5	26.4	13.0	36.6	34.0	30.3	52.4	24.5
After planting	13.3	17.4	14.2	23.4	9.9	18.0	30.7	24.2	12.7	15.3	17.6
Fertilizer: appl. method											
Broadcast (ground)	72.1	50.0	56.9	33.9	47.2	72.3	25.8	45.9	49.7	29.2	50.9
Broadcast (air)	.8	.5	.9	.7	0.0	2.3	1.2	1.2	1.0	1.2	.8
Chemigation	0.1	0.2	0.0	0.3	0.0	1.3	2.4	0.0	0.0	0.0	0.4
Banded	5.5	27.4	14.2	44.5	28.4	10.7	35.8	33.9	26.8	53.1	23.6
Foliar	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.0	0.0
Injected (knifed in)	21.5	22.0	28.1	20.6	24.5	13.3	34.9	18.9	22.6	16.5	24.2
Herbicide: timing											
Before planting	54.2	42.8	43.4	13.6	21.2	47.8	12.2	17.8	24.0	11.4	32.9
At planting	7.4	17.7	7.4	14.8	8.0	24.9	40.4	22.0	20.0	5.4	15.5
After planting	38.5	39.5	49.2	71.6	70.8	27.3	47.4	60.2	56.0	83.2	51.5
Herbicide: appl. method											
Broadcast (ground)	93.9	81.8	88.7	70.2	76.9	84.9	50.3	79.6	66.1	82.4	79.2
Broadcast (air)	1.7	0.0	1.5	0.0	0.7	1.4	3.0	6.3	71.3	1.2	2.0
In-furrow	0.4	2.0	0.0	0.5	1.5	0.9	3.1	0.7	0.8	2.0	1.2
Chemigation	0.0	0.0	0.0	0.7	0.0	0.0	0.2	0.0	0.0	0.0	0.0
Banded	1.8	3.7	6.8	9.0	8.8	8.4	41.4	7.6	19.0	3.6	11.4
Directed spray	2.1	12.5	3.0	19.6	12.1	4.4	2.0	5.8	6.7	10.9	6.2
Insecticide: timing											
Before planting	5.5	6.5	10.2	0.6	2.6	35.5	2.6	10.7	8.8	0.0	4.0
At planting	78.2	82.3	93.1	96.9	89.7	54.8	49.3	75.0	76.5	90.9	76.5
After planting	16.4	11.3	5.8	2.5	7.7	9.7	48.2	14.3	14.7	9.1	19.5

Insecticide: appl. method											
Broadcast (ground)	22.1	25.0	7.1	13.1	7.7	50.0	7.4	33.3	18.8	7.2	14.3
Broadcast (air)	0.0	0.8	0.5	0.0	0.0	0.0	26.0	1.2	6.3	0.0	6.7
In-furrow	18.3	30.6	30.1	25.6	48.7	36.7	19.6	27.4	6.3	28.9	24.9
Chemigation	0.4	0.0	0.0	0.0	0.0	0.0	1.5	2.4	0.0	0.0	0.5
Banded	58.7	40.3	60.7	58.8	41.0	13.3	45.6	34.5	68.8	63.9	52.5
Directed spray	0.4	3.2	1.5	2.5	2.6	0.0	0.0	1.2	0.0	0.0	1.0

[1]Percents for a practice may add to more than 100 since an acre can be treated more than once with a same or a different practice.
[2]Revised planted acres, June 1994.

Source: USDA. ERS. Data updates from the Resources and Technology Division. *RTD Updates: Chemical Use Practices*. Number 2; July 1994, p. 2.

Table 6. U.S. Pesticide Use on Corn, Soybeans and Cotton: Pounds of Active Ingredients (1000s).

Sources:

(1) USDA. ERS. Natural Resources and Environment Division. "Pesticide and Fertilizer Use and Trends in U.S. Agriculture." *AREI Updates*. Agricultural Economic Report No. 717. May 1995.

(2) Ohio Agricultural Research and Development Center. "Pesticide Use on Major Crops in the North Central Region, 1978." Research Bulletin 1132. July 1981.

(3) USDA. ERS. Natural Resource Economics Division. "Pesticide Use on Selected Crops, Aggregated Data, 1977-80." Agriculture Information Bulletin No. 494. June 1985.

(4) Swanson, Jeffrey A. and Dale C. Dahl. *The U.S. Pesticide Industry: Usage Trends and Market Development*. Staff Paper Series P89-5. Department of Agricultural and Applied Economics. University of Minnesota. January 1989.

(5) USDA. ERS. National Agricultural Statistics Service and Economic Research Service. *Agricultural Chemical Usage 1995 Field Crops Summary*. March 1996. (Also year 1991, 1992, 1993 and 1994). (Adjusted for total crop acreage.)

5. ***Fuel***

In addition to the indirect role of fertilizer and pesticides in accounting for on-farm energy consumption, additional data exists on farm energy use for fuel and for irrigation. Fuel purchased for farm use includes the fuel requirements of livestock operations, as well as crop production. Total farm use of gasoline, diesel and LPG (liquid propane gas) was 5.8 billion gallons in 1995. When examined over time, on-farm gasoline consumption has fallen from a peak of 4.5 billion gallons in 1975 to current levels of 1.4 billion gallons (Figure 3). LPG has also shown a slow downward trend, falling from 1.4 billion gallons in 1974 to 0.8 billion gallons in 1995. Diesel fuel use has been uneven, but has clearly been the primary substitute for gasoline, and has risen especially in the 1990s, from 2.5 billion gallons in 1989 to 3.6 billion gallons in 1995 (see Appendix Table 1).

Energy for irrigation can be decomposed by crop, although the price of energy and the type varies from area to area. Corn crop irrigation covered 9.3 million acres in 1994, the last year of data (Table 7, Figure 4). On average 15.5 inches of water were applied over the growing season, and 144.2 million acre inches of water were used. Nebraska dominates the statistics with 4.6 corn million acres under irrigation, supplied almost exclusively by on-farm wells. Irrigation covered 11.7 percent of the total U.S. corn crop in 1994. Soybean irrigation covered 2.6 million acres in 1994. Arkansas alone has more than a million acres, again supplied primarily by on-farm wells. Over the growing season 19.4 million acre inches of water were applied to soybeans in the U.S., at an average rate of 7.5 inches per acre (see Figure 5). Cotton had 4.3 million acres under irrigation in 1994 or 31 percent of the acreage base. Texas and California had the most acres, with 1.8 million and 1.0 acres

Figure 3. U.S. Farm Fuel Use 1974-1995.

Source: USDA. ERS. National Resources and Environment Division. "Farm Fuel and Ethanol." *AREI Updates*. Number 16; December 1996.

Table 7. U.S. Irrigation Practices on Corn, Soybeans, and Cotton.

Source: USDA. ERS. *Irrigated Land in Farms*. December 1993; and
USDA. ERS. *Irrigation Water Use, 1994*. August 1996.

Figure 4. U.S. Corn: Irrigated Water Use 1969-1994.

Source: USDA. ERS. *Irrigated Land in Farms*. December 1993; and
USDA. ERS. *Irrigation Water Use, 1994*. August 1996.

Figure 5. U.S. Soybean: Irrigation Water Use 1969-1994.

Source: USDA. ERS. *Irrigated Land in Farms*. December 1993; and
USDA. ERS. *Irrigation Water Use, 1994*. August 1996.

Figure 6. U.S. Cotton: Irrigation Water Use 1969-1994.

Source: USDA. ERS. *Irrigated Land in Farms*. December 1993; and
USDA. ERS. *Irrigation Water Use, 1994*. August 1996.

respectively. The average acre got 21.5 inches of water over the 1994 growing season, with 92.5 million acre inches in total use. Off-farm water suppliers are more important to California agriculture than Texas, where on-farm wells supply much of the irrigation (see Figure 6). Irrigation on corn in million acre inches has remained at roughly the same levels since 1979, while irrigated soybean acreage increased to a high of about 30 million acre inches in 1989 and then declined to 19.5 million acre inches in 1994. Cotton, like corn, reached its highest irrigation levels in 1979, and rested in 1994 at 92.5 million acre inches.

6. ***Genetic Improvement***

A final source of productivity growth in historical terms has been seed and the genetic information it contains. Hybridization of corn began in the 1920s, and contributed significantly in the post-war period to rapid increases in yields per acre, although traditional plant breeding and genetic gain are often understated relative to hybrid seed. The foundations of this process resulted from the application to corn breeding of Darwin's theories of natural selection and Mendel's laws of genetic variation, beginning at the turn of the century. During 1908-11, George Shull, a botanist in New York, developed inbreeding of corn based on observations that if inbred strains were crossed (hybrid), the resulting heterosis would produce more vigorous, higher-yielding varieties. Unfortunately, the inbred strains themselves were very low yielding, making commercial seed production uneconomical. In 1918, it was discovered that if two single-crossed hybrids were themselves crossed (instead of two inbred lines), the resulting double-cross yielded well, and the single-cross parents were themselves sufficient seed producers to make the enterprise commercially viable. By the 1940s, in addition to the Wallace family's Pioneer company, thousands of family-farm seed companies had sprouted, so that hybrid seed planting expanded from less than one percent of area planted to corn in 1934 to over 90 percent of the Iowa Corn Belt by the end of World War II (Dowswell, et. al., 1996, p. 55).

An important explanation for the rapid growth of these seed operations is that corn hybrids have genetically closed pedigrees, protecting against copying, and must be regenerated each year from inbred parental crosses to avoid loss of vigor in the second generation. This created incentives to continually recombine varieties, but captured the benefits from this experimentation for the experimenting seed company, resulting in systems in which profits are regularly plowed back into the development of new varieties, continually pushing out the frontiers of yield potential. Adding to this impetus were the public-sector activities of U.S. Land Grant Universities and the U.S. Department of Agriculture, which together developed many of the new inbred lines and hybrids, but then allowed private companies to retain control over actual seed production.

Another key linkage is from plant breeding to fertilizer use. Until the mid-1950s, many newer corn hybrids had responded poorly to higher nutrient levels, despite the ready availability and low cost of nitrogen in the wake of a post-war production glut of ammonium nitrate. In the mid-1950s and 1960s, corn hybrids and cotton varieties reached the market which did not develop the weak stalks of previous hybrids when more heavily fertilized. As a result, still higher yields were achieved.

One of the challenges facing the newly developed, genetically-engineered seed varieties, including Bt-corn and cotton and Round-up Ready soybeans, is how to capture the full value of recombined genetic material, which does not dissipate after one generation. Innovating companies have attempted to attach intellectual property protection to avoid having their genetic material bred into other seed. This is an important future question for breeding efforts.

In the case of herbicide resistent soybeans, even critics have acknowledged that they can help phase out older, more environmentally damaging herbicides and make integrated week management more attractive to farmers, although reliance on a more narrow range of chemicals, some fear, could lead resistance to develop in weeds as well (Krimsy and Wrubel, 1996, p. 54).

In the case of insect-resistent crops such as Bt corn and cotton, a primary challenge will be to control and manage resistance and to relate these crops to integrated pest management strategies. J. R. Bradley (1995), in a recent review of Bt cotton, suggests that Bt cotton and non-Bt cotton fields be arranged so that sufficient refugia are maintained for the non-Bt selected insects. Clearly, these and other issues confronting new biologically engineered crop varieties pose important new challenges to the seed industry.

B. Input Substitution: Future Possibilities and Trends

One of the most difficult problems in evaluating changing technologies and their linkages to productivity concerns the capacity to substitute one type of input for another in order to maintain or increase output. As an historical review makes clear, gains in agricultural productivity in the U.S. have been driven by the substitution of various inputs for labor: harnessing mechanical as well as human capital, fertilizers, pesticides, and seeds to increase output per unit of labor input. The problem of attributing productivity changes to a single input or subset of inputs is that all of these technical, institutional, mechanical, and other inputs have interacted and worked together. It is now widely recognized that farming is a ***system***, and that systemic interactions account for large changes in production which are more than the sum of the individual input contributions.

Consider fertilizers and pesticides. If all inorganic nitrogen fertilizer, herbicides, insecticides and fungicides were removed from U.S. crops, Knutson, et. al. (1990) estimated that U.S. corn yields would fall 53 percent nationally, soybeans 37 percent, and cotton 62 percent. Resulting increases in total estimated economic costs for corn, soybeans and cotton respectively of 61, 45 and 118 percent revealed the reliance of these crops on these inputs. However, such analysis does not account for the ***substitution*** of other technologies or inputs as systems of production change. For example, integrated pest management (IPM) and alternative crop rotations restoring nitrogen to the soil would surely be more widely adopted if these chemical inputs were entirely removed. Hence, the reliance of agriculture on any given technological combination at any given time is easily overestimated.

The latest chapter in this process of substituting inputs is agricultural biotechnology. In many respects, agricultural biotechnology is the application of human capital to seed technology to create new genetic information and plant characteristics. The deeper question of this study, to be pursued in future analysis, concerns the possible substitution of this genetic information for mechanical and fuel inputs, fertilizers and pesticides that have been associated with negative environmental impacts. At the farm level, if such substitutions can maintain or even increase corn, soybean and cotton yields while reducing expenditures for fuel, fertilizer and pesticides, then profits can be enhanced as these input costs decline. Equally important, reductions in the use of these inputs in the aggregate may result from their complementarity with tillage practices that conserve soil, and more precise applications of fertilizers and pesticides that target applications more narrowly, reducing overall usage. These ***systemic*** interactions between biotechnologies, tillage practices, and input applications are likely to have wider and more profound environmental impacts than the simple change in seed varieties, taken in isolation, would suggest.

In order to evaluate these future possibilities and trends, it is first necessary clearly to establish the historical use of these inputs for corn, soybeans and cotton, and to set a benchmark against which substitution possibilities and environmental impacts can be estimated. We turn now to a review of this information, focusing on fertilizer, pesticides and fuel on each of the three crops over the last 30 years. These input use levels will set the stage for the detailed examination of regional production and the potential impacts of biotechnology in Part II of the larger study.

C. Commodity-Specific Analysis, 1964-1995

1. ***Corn***

(a) Area Planted and Factors Affecting Yields

U.S. corn yields have followed a strong upward trend since 1951, averaging an increase of nearly 2 bushels per year for the last 44 years (Figure 7). A slightly less impressive assessment of corn yield trends results from analysis of the period from 1975 to 1996, during which corn yields increased at a rate of 1.54 bushels per acre per year (compared with nearly 2 bushels for the period 1951-95). The fit of this trend line is less pronounced due to the peaks and valleys involved, with an R^2 of .37 compared with .87 for the longer period. Even so, it is reasonable to say that corn yields have been both more variable and have risen less rapidly in the 1975-95 period.

Corn yields averaged just 37 bushels per acre in 1951, while the record high yield was 139 bushels in 1994. Hybrid seed development is often emphasized as a main cause, and progressed steadily until 1970 when corn blight reduced yields late in the season. Blight-resistant hybrids were substituted quickly. Single-cross hybrids, produced a few years later especially by Pioneer Hi-Bred, were found to out-yield earlier combinations. Evidence of the payoff to seed innovation was that Pioneer, which had about the same market share as DeKalb in 1974, quickly expanded to around 40 percent while DeKalb fell from the mid-20 percent area to as little as 7-8 percent in the 1980s.

Yet a primary difficulty in attributing yield increases to any particular factor, as noted above, is the fact that inputs work together, so that the influence of one may be confounded with another. It is relatively easy to find fertilizer specialists claiming as much as half a given yield increase as due to nitrogen, weed scientists claiming half for pesticides, and plant breeders claiming half for themselves, without yet accounting for weather! In response to this confounding situation, Cardwell (1982) attempted one of the few studies in which regression analysis was carefully used to aportion the specific influence on corn yields of hybrid seed, fertilizer, and other effects over fifty years of Minnesota corn production (1930-1979) (Cardwell, 1982). Dividing his analysis into decades, Cardwell showed that corn production began yield advances in the 1930s with the adoption of hybrids, but that genetic gain in yield potential through plant breeding has been at least as important as hybrids per se. Together, over the entire fifty-year period, Cardwell estimated that plant breeding and hybrids together accounted for 58 percent of the net increase in yields. A second important explanatory variable was fertilizer, especially from the mid-1950s to the 1960s and 1970s. The net effect of fertilizer (primarily nitrogen) was to explain 19 percent of yield gains over the entire period. A third factor was pesticides, especially herbicides, beginning in 1947 with the introduction of 2,4-D (2, 4-dichlorophenoxy acetric acid), and in 1957 of atrazine [2-chloro-4-(ethylamino)-6-(isopropylamino)-2-triazine). By permitting earlier planting dates and season long week control, pesticides were credited with 23 percent of yield increases over the entire period. Other variables contributing to yield increases were improvements in plant density (due largely to increases in fertilization) earlier planting dates (related to herbicide adoption and hybrid seed), row spacing, planting patterns, drainage, and rotation with soybeans. At the same time that these factors were positively affecting yields, others were negatively affecting them. These included yield losses due to corn rootworm infestation related to continuous corn cropping, the impact of the European corn borer after 1940, and soil erosion. All told, these factors were estimated to have reduced total yields over the period by 23 percent with an additional 23 percent of reductions unexplained (Cardwell, 1982). A summary of these data is shown in Table 8. No more recent decomposition of these effects has been undertaken.

Planted acres of corn varied from a high of about 85 million acres in the mid and late 1970s to a low of about 60 million acres in 1983, the year of the Payment-in-Kind (PIK) program (in which farmers were paid in-kind subsidies not to plant corn so as to reduce large surpluses). A drop in planted acres during the 1960s was perhaps due to rising soybean acreage. Despite the variation in planted acres, there has not been a substantial trend upward or downward; variation has occurred around an average of about 75 million acres per year since 1964. Acres planted but not harvested as grain, due to weather, abandonment, drought or other reasons (mainly use as silage) have been in the range of 7 million acres per year (Figure 8 and Appendix Table 2).

The relative stability of land in corn production has been accompanied by an upward trend in production itself, owing largely to the yield increases noted above. Production rose steadily throughout the 1960s and 70s, during which variability in weather effects was significantly less than after 1980 (Tiegen and Thomas, 1995, p. 12). In addition to weather events, such as the droughts of 1983 and 1988 and the floods of 1993, policy-induced changes in acres planted due to PIK in 1983, and high levels of government acreage retirement programs in 1985, 1986 and 1987 (combined with heavy enrollments of corn acres in the Conservation Reserve Program beginning in 1985) all contributed to reductions in production. As a result of these forces, production in the 1980s has been significantly more variable than in the 1960s and 1970s (Figure 8). These yearly fluctuations are greater in some cases than the ***total*** output of corn in some earlier years.

Table 8. 1930 - 1979 Minnesota Corn Yields Attributable to Various Inputs and Environmental Factors.

Yield Increasing Factors	Yield Percentage Gain/Loss
Hybrid Varieties/Genetic Gain	+58
Fertilizer (N)	+19
Herbicides	+23
Plant densities	+21
Earlier planting dates	+ 8
Drilling vs. hill dropping	+ 8
Fall plowing	+ 5
Row spacing	+ 4
	144
Yield Decreasing Factors	
Corn following corn	
(corn rootworm)	– 3
(interference effect)	– 7
Corn borer	– 5
Soil erosion	– 8
Other (residual)	–23
	46

Source: Cardwell, V. B. "Fifty Years of Minnesota Corn Production: Sources of Yield Increase." *Agronomy Journal* 74(Nov.-Dec. 1982): 984-990.

Figure 7. U.S. Corn Yields 1951-96.

Source: USDA. Agricultural Statistics Board. National Agricultural Statistics Service. *Corn Yearbook*. 1996.

Figure 8. U.S. Corn: Acreage and Production 1951-1995.

Source: USDA. Agricultural Statistics Board. National Agricultural Statistics Service. *Corn Yearbook*. 1996.

(b) Fertilizer Use

It is not only the downward effects of weather and government land retirements on production that have led to growing variability: it is also the upward effects of more and better agricutural inputs such as fertilizers, pesticides and seeds, which in good weather years drive yields to new heights. In the case of fertilizer, about 95 percent of all corn acres received nitrogen treatments, with phosphate and potash running in the 75 to 80 percent range over most of the 1964-96 period (Figure 9). What is more striking about corn fertilizer use is the application rates of nitrogen in pounds per acre, which rose from about 60 pounds in 1964 to a high of 140 pounds in 1985, and remain in the range of 130 pounds (Figure 10). This doubling of nitrogen applications was matched in potash, with applications increasing from about 40 pounds per acre in 1964 to over 80 pounds per acre during the 1980s and 1990s. Phosphate application rates rose from about 40 pounds per acre in 1964 to about 60 pounds in the mid-1970s and have remained at roughly that level -- about a 50 percent increase in pounds per acre over the period (see Appendix Table 3). These application rates, as noted above, are related to successful development of hybrid corn varieties with the capacity to utilize additional nutrients. Total corn fertilizer use in billions of pounds reflects the same trends (Figure 11), with total nitrogen use growing from a little more from 3 billion pounds to as much as 11.3 billion pounds in 1985, and remaining in the range of nine billion pounds in the 1990s. Total potash and phosphate use rose from about 2 billion pounds in 1964 to their highest levels in the late 1970s and early 1980s, reaching over 6 billion pounds for potash and about 5 billion pounds for phosphate. In total, corn accounts for almost half of total plant nutrient use, compared with about 14 percent for wheat, the second most fertilized U.S. crop, and soybeans, which account for about 6 percent (Andrilenas and Vroomen, 1990). Unfortunately, many nitrogen recommendations for corn are based on monoculture trials, rather than on trials with rotations of soybeans or other crops. The result is to recommend applications higher than would be the case if credit were given to the nitrogen fixed by the legumes (Franzleubbers, et. al., 1994). When soil-specific tests are conducted to relate applications of N to corn on a field-specific basis, and yield goals are based on multi-year averages, N application rates can be as much as 30 pounds per acre below the recommended rate without affecting economic returns (Vanotti and Bundy, 1994).

In sum, total fertilizer use on corn peaked and then declined after the early 1980s, although pounds per acre remained relatively constant, as did the percent of acres fertilized with nitrogen (the percent fertilized with phosphate and potash declined slightly). Yet yields continued an upward (albeit uneven) increase, suggesting that fertilizer alone was only one factor among many. Part of the further explanation was that weed and pest control on corn became increasingly sophisticated, part of the systemic increase in productivity noted above.

Figure 9. U.S. Corn: Percent Acres with Fertilizer Applied 1964-95.

Figure 10. U.S. Corn: Fertilizer Application Rate 1964-95.

Figure 11. U.S. Corn: Total Fertilizer Use 1964-95.

(c) Pesticide Use

Total pesticide applications on corn, by active ingredients (ai), include herbicides, insecticides and fungicides. Herbicides used on corn rose from about 25 million pounds in 1964 to a high of 243 million pounds in 1982, and fell to about 221 million pounds in 1992 and 186 million pounds in 1995. This was nearly a ten-fold increase in active ingredient of herbicides applied to corn over the entire period (Figure 12). Per acre applications rose dramatically from 1964 to about 1980, basically tripling, then leveled off and began declining slightly in the 1990s. The specific herbicides used on corn changed, however. In 1964, atrazine and 2,4-D were the most heavily used. By the early 1990s, atrazine was still the leading herbicide, with 55 million pounds in 1992, followed by metolachlor with 41 million pounds, alachlor with 40 million pounds and cyanazine with 27 million pounds, while 2,4-D declined from 15 million pounds in 1996 to 2.8 million pounds in 1992 (Lin, et. al., 1995).

Insecticides are used on corn mainly to control corn rootworm larvae. In 1964, about 16 million pounds of insecticides were applied to corn, rising to almost 36 million pounds in 1980 and declining to about 14 million pounds in 1995 (Figure 14). Until 1979, Aldrin was the most commonly used insecticide, when it was canceled due to carcinogenicity, bio-accumulation and wildlife concerns. In the mid 1970s, carbofuran was the most heavily used, but has declined due to its acute toxicity to birds. In 1994, it was canceled in its granular formulation for corn rootworm. By 1992, chlorpyvifos and terbufos had become the most heavily used insecticides on corn, accounting for 68 percent of total insecticide use. Fungicide use on corn is negligible, and is applied mainly on fruits and vegetables.

In the case of both pesticides and fertilizer, especially herbicides and nitrogen, application timing and methods can greatly influence total use levels. Lin, et. al. (1995) report that switching from pre-planting to after-planting applications and from broadcast to band applications can reduce nitrogen use by 4 and 57 pounds per acre, respectively. Banding and after-planting application of herbicides can also reduce use, although before-planting herbicides are often older products with expired patents, and therefore cheaper to use. Trends toward the more precise application of pesticides, and their increased efficacy, are consistent with the continued increases in yields in the 1990s even as total pounds of active ingredients fell.

Figure 12. Pesticide Use in Corn Production 1964-1995.

(d) Fuel and Energy Use

The energy input to corn production occurs both indirectly as a result of fertilizer and pesticide use, as well as directly for fuel and other energy used on the farm to power tractors, combines, drying and irrigation facilities. As described above, the internal combustion engine was the central factor increasing reliance on petroleum fuels on-farm, although this reliance was also systemically related to other inputs. For example, in addition to utilizing fertilizer and chemicals more efficiently, hybrid varieties of corn hastened the shift to mechanization, because hybrid corn stalks were sturdier, stood in the field longer if harvests were delayed, and were thus able to be cut and harvested more easily by machinery. As mechanization increased, it also became easier to apply fertilizers and chemicals, creating an interactive synergy pushing forward yields (Hudson, 1994, p. 171; Crabb, 1947, p. 291). In the 1970s, short season hybrids also pushed the Corn Belt northward into Minnesota and Wisconsin as dairy farms were replaced with cash grain, furthering the demand for mechanical harvesters and thus fuel.

In a well-known critique of the energy efficiency of corn production, Pimentel (1973) concluded that the ratio of crop energy yield to input energy (excluding solar) had declined between 1945 and the 1970s: that in effect agriculture was becoming more and more dependent on scarce hydrocarbon inputs. In the early 1980s, Smil, et al. (1983) extended and refined this analysis to account for technological improvements in the energy efficiency of fertilizer manufacture as well as improved efficiency in tillage methods and farm machinery. In addition, they noted that Pimentel had failed to exclude fuel used for farm families as distinct from field operations, and had double-counted electricity use in some practices such as irrigation. Figure 13 shows the boundaries of inputs used in Smil, et. al.'s analysis.

Figure 13. Boundaries of Inputs Included in Energy Analysis of U.S. Grain Corn.

Source: Smil, et. al., 1983, p. 6.

An example of technological improvements affecting energy use in corn production is the self-propelled corn combine, which strips the ears from the stalk, removes the kernels, stores them, and dumps the cobs and hulls so that a 70-bushel acre can be harvested in 15 minutes -- one-tenth of the time required by older mechanical pickers. Energy for field operations for all crops was also affected by the increasing reliance on diesel fuel and the declining role of gasoline. By the mid-1970s, total gasoline use in corn production for all field operations[1] required 278 million gallons of gasoline,compared with 392 million gallons of diesel fuel and 47 million gallons of LPG (Smil, et. al., 1983, Table 4.2). Table 9 shows estimates by Smil, et. al. of gallons per acre of fuel used from 1945-1974 for field operations, while Table 10 shows energy required for irrigation; both compare them to Pimentel, et. al.'s earlier estimates. Because Pimentel, et. al. included farm family automobiles and failed to distinguish among fuel types, his estimates were over twice those of Smil, et. al. for machinery, fuel and irrigation. The trend in total fuel energy per acre of corn shown in Table 9 is essentially constant in the Smil, et. al. study, while it increases by more than half in the Pimentel, et. al. study. When energy costs of machinery to farm one acre of corn were compared, as shown in Table 11, Smil, et. al. again found about half of the energy use reported by Pimentel, et. al. (Table 11). These machinery differences were due primarily to the shorter depreciation schedules used by Pimentel, et. al. (10 versus 12 years), the economies of size resulting from larger fields, and the increased horsepower and lighter construction of more recent farm implements (Smil, et. al., 1983, p. 50).

[1]Preplanting, planting, cultivating, fertilizer and pesticide applications, harvesting and farm trucks.

Table 9. Machinery Fuel Consumed in Grain Corn Farming, 1945-1974.

Source: Smil, et. al., 1983, p. 44.

Table 10. Energy Required to Irrigate One Harvested Corn Acre, 1945-1974.

Source: Smil, et. al., 1983, p. 45.

Table 11. Energy Equivalent of Machinery Used in Farming One Acre of Corn, 1945-1974.

Source: Smil, et. al., 1983, p. 61.

In a general evaluation of trends in energy use for corn production, including fertilizers and pesticides as well as fuel, a basic finding appears fairly clear: total energy use per acre of corn production is not growing, but neither is it falling; rather, the types of energy inputs are changing. Specifically, nitrogen fertilizer is accounting for more than twice the energy inputs of the early 1960s, while fuel and machinery is falling to less than a third of previous input levels. Pesticides account for less than 5 percent of total energy used, although they can be substantially reduced by more precise applications. These trends indicate the extent to which substitutions in the system of corn production are possible, and the fact that many factors are changing over time. This makes attributions of the significance of single factors fraught with the possibility of overstatement, but encourages a view of the flexibility of farming systems and the possibility of more and future substitutions.

(e) Per Acre Input Expenditures

The quantities of inputs used on corn tell only part of the story of how various inputs are substituted for one another. Inputs obviously vary in price, resulting in incentives to shift from one to another. Higher fuel costs generate incentives to reduce passes over the field, for example, just as higher nitrogen or phosphorus prices stimulate incentives to test for nutrient levels and to apply these nutrients more precisely. Cash costs for select production inputs can be expressed in either nominal or real terms. Nominal prices reflect the buying power for the current year in which the expense occurs. Real costs reflect the buying power of a base or index year. One way to convert current year input prices is to divide them by the index of prices paid by farmers for each input. The USDA prices paid indices measure average national price changes for various input groups -- these are not, however, crop specific.

Figures 14 and 15 show both nominal and real cash costs for fertilizer, chemicals, energy and seed on corn acres (see Appendix Table 4). Corn average cash expenses for fertilizer were $55.85 per acre in 1995. In the constant purchasing power of 1992 dollars, the same fertilizer application would cost $47.74 per acre. Hence, when expressed in the purchasing power of the index dollar (i.e., in real terms), fewer dollars are needed to purchase an equal amount of product. By contrast, seed expenditures rose in both nominal and real terms between 1975 and 1995.

Figure 14. U.S. Corn: Select Cash Costs (current year dollars).

Sources: "Revised Prices Received and Paid Indexes, United States, 1975-93; for Base Periods 1910-14=100 and 1990-92=100." Statistical Bulletin Number 917, National Agricultural Statistics Service, USDA, January 1995.

"Agricultural Prices," National Agricultural Statistics Service, USDA, March 1997.

"Farm Production Expenses," National Agricultural Statistics Service, USDA, Various Annual Issues.

Figure 15. U.S. Corn: Select Cash Costs (constant 1992 dollars).

Sources: "Revised Prices Received and Paid Indexes, United States, 1975-93; for Base Periods 1910-14=100 and 1990-92=100." Statistical Bulletin Number 917, National Agricultural Statistics Service, USDA, January 1995.

"Agricultural Prices," National Agricultural Statistics Service, USDA, March 1997.

"Farm Production Expenses," National Agricultural Statistics Service, USDA, Various Annual Issues.

Overall, when the share of each of these inputs in total expenses is examined in real terms, fertilizer costs have declined somewhat since the mid-1980s, and chemical costs have trended slightly upward since the mid-1970s. Energy costs have risen in constant 1992 dollars from a low of 11.86 dollars per acre in 1986 to 20.36 dollars per acre in 1995. From the point of view of farm usage, these trends suggest incentives to economize on the use of farm chemicals and especially on energy, while maintaining current levels of fertilizer use per acre.

2. ***Soybeans***

(a) Acreage and Factors Affecting Productivity

Soybean yields averaged 20 bushels per acre in 1955, and have increased more than a third of a bushel per year on average every year since (Figure 16). The record high was 41 bushels per acre in 1994. Like corn, yields have fluctuated around a rising trend. Unlike corn, this trend increases in the period 1975-96, when soybean yields increased by .44 bushels per acre compared with .35 bushels per care for the period 1955-95. This recent increase is, however, less tightly fitting, with an R^2 of .53 compared with .79 for the longer time period. Overall, however, soybean yields, despite their variability, may be on a slightly increasing slope upward.

Soybeans are central to the cropping cycles of much of the agricultural United States. Together, the Corn Belt and Delta states accounted for 37 million of a total 58.2 million acres of soybeans in the U.S. from 1990-94, and 40 million out of 63.4 million acres in the U.S. in 1996. The rest were largely grown in the Lake states (8.4 million acres in 1996), Northern Plains (8.5 million acres in 1996) and Appalachian states (4.0 million in 1996) (USDA, ERS, AREI, September 1996). But the centrality of soybeans is a relatively recent development. Before World War II, soybeans were raised on a limited basis for "green manure" -- as a legume to provide a nitrogen base for corn, cotton, or tobacco. The Chicago Board of trade established the first contract for soybeans in 1936, when soybean acreage stood at 7 million acres, about 10 percent of that year's corn acreage (Soya Bluebook Plus, 1995). Since World War II, soybean acreage has grown steadily as many new uses for the crop have developed. The most important of these uses -- for soybean oil and

Figure 16. U.S. Soybean Yields, 1955-96.

Source: USDA. Agricultural Statistics Board. National Agricultural Statistics Service. *Oil Crops Yearbook*. October 1996.

meal -- rose dramatically as both processed foods such as margarine and animal feeds grew in response to hog and cattle feedlots. In the interim years, increased mechanization and declining use of animal draft, especially horses, reduced the demand for oats, which acreage was often converted to soybeans. Government programs restricting corn acreage also encouraged soybeans to be planted in their place. Since soybeans are planted on the same soils and at roughly the same time as corn, and are suited to much of the same planting and harvesting equipment, acreage expanded first in the Corn Belt (Hudson, 1994, p. 163).

In 1955, planted acres of soybeans stood at 20 million, growing steadily into the 1960s (Figure 17). In 1973, President Nixon, concerned over possible soybean shortages in the domestic market, implemented a brief embargo on soybean exports, upsetting trade especially with Japan, although planted acres, production and exports continued to grow throughout the 1970s. In part because soybeans were never designated a "basic" farm commodity under U.S. farm policy, they were not directly subsidized or subject to acreage controls, although they received loan rate support. From the farmer's point of view, this discouraged increases in planted acres in the 1980s and early 1990s, when corn, cotton and other crops were receiving high levels of price support, although higher loan rates did encourage some acreage expansion. Planted acres trended downward from a high of about 71 million acres in 1979 to current levels of about 65 million acres. Since soybeans can almost always be harvested for some use, few acres planted are not harvested (Figure 17).

Production of soybeans, like corn, has been more variable in the 1980s and 1990s than in the 1950s and 1960s, and has been affected by the same weather events (Figure 18 and Appendix Table 5). Weather effects on soybeans in two major producing states, Iowa and Indiana, for example, became more variable in the 1980s. When the impact of technology is separated from weather effects on yields, Teigen and Thomas, Jr. (1995, p. 24) report that it too accounted for increasing amounts of yield variation in the period between 1978 and 1987, and accelerated thereafter. This technology included the application of fertilizers, herbicides, fuel, machinery and seeds. Unlike corn, soybeans are not subject to major disease or insect problems, so that herbicides are far more important than insecticides. Since soybeans are nitrogen fixing, their nitrogen nutrient requirements are also much less than corn. Conventional wisdom on soybean yields in the 1960-80 period was that genetic improvements were negligible, but increased in the 1980s and 1990s. Many new soybean seed varieties have been certified from 1991-94 (a total of 164 varieties), a five-fold increase over the period 1961-64 (USDA, AERI #14, 1995). Generally, farmers have learned to grow soybeans better, optimizing the use of fertilizer and especially chemical and energy inputs.

Figure 17. U.S. Soybean Acreage and Production 1955-96.

Source:

(b) Fertilizer

From 1964-95, a maximum of about 40 percent of planted soybean acres received fertilizer; this maximum occurred in 1979. Since then, the percentage of planted acres receiving treatment has fallen to current levels of around 20 percent of total (Figure 18). Nor does this appear to be a regional or North/South phenomenon. About the same percentage of acres received potash and phosphate in the North and South in 1995, with slightly more nitrogen applied in the Southern states (USDA, AREI #2, May 1996). Soybeans' share of total nutrient consumption increased from one percent on 1964 to 8 percent at the high point in 1979.

Even so, the overall application rate of fertilizers to soybeans has definitely increased since 1964, most especially in potash (Figure 19 and Appendix Table 6). When examined on a per acre basis, application rates have increased for potash from about 37 pounds per acre in 1964 to about 84 pounds per acre in 1995, almost 10 pounds per acre more than in 1979. Phosphate use has gone from 30 pounds per acre in 1964 to a high of about 54 pounds per acre in 1995, with nitrogen climbing from about 14 pounds per acre in 1964 to about 28 pounds per acre in 1995 (Figure 20).

Total fertilizer applications on soybeans have risen largely as a function of total acreage, although nitrogen applications, for the reasons stated above, have remained low. Total potash and phosphate applications rose throughout the 1960s and 1970s, peaking in 1979 and declining thereafter (Figure 19). Supplementary nutrients on soybeans are far less common than on corn, however.

Figure 18. U.S. Soybeans: Percent Acres Fertilizer Applied 1964-95.

Figure 19. U.S. Soybean: Total Fertilizer Use 1964-95.

Source:

Figure 20. U.S. Soybean: Fertilizer Application Rate 1964-95.

(c) Pesticides

As noted above, pesticides used on soybeans are mainly herbicides, with insecticide use relatively minor. In 1995, soybean crops received 69 million pounds of active ingredient, of which virtually all were herbicides, with only 515,000 pounds of insecticides and 13,000 pounds of fungicides applied. Herbicide use on soybeans peaked at about 125 million pounds in 1982, with application rates of 1.83 pounds per acre (Figure 21 and Table 12). The percentage of soybean acres treated with herbicides rose from 27 percent in 1966 to 95 percent in 1982, but fell so that by 1992 total usage had declined to 59 million pounds and application rates to 1.14 pounds, although the percentage of treated acres remained constant at about 95 percent. It is probable that increased yields in the late 1980s and 1990s have resulted from improvements in varieties and the greater efficacy of herbicides, which have changed considerably since the 1960s.

Lin, et. al., (1995) report that trifluralin was the most heavily used herbicide through the 1964-92 period. It is applied as a broad-cast, pre-plant, soil-incorporated treatment to control many broadleaf and grass weeds. Chloramben was used extensively during the 1960s and up to 1982. Since that time, its use has dropped dramatically. Chloramben is generally applied as a band application in the crop row at planting time. Alachlor, by contrast, is generally applied as a preemergence broadcast treatment.

In the late 1980s, several new herbicides were introduced for weed control in soybean production. These included chlorimuron, imazaquin, and imazethapyr. Chlorimuron is applied postemergence at a rate of 0.02 to 0.03 pound per acre to control broadleaf weeds. Imazaquin and imazethapyr can be applied pre-plant, preemergence, and postemergence primarily for broadleaf weed control, although some grass weeds are also controlled when applied pre-plant or preemergence. Imazaquin is applied at out 0.1 pound and imazethapyr at 0.06 pound per acre. In addition, growers in recent years have increased their use of the postemergence grass herbicides, fluazifop and sethoxydim, which are applied at 0.14 pound and 0.2 pound per acre, respectively. The above materials have substituted for alachlor, which is applied at 2.0 pounds per acre, and thus accounted in part for the downward trend in soybean herbicide use.

Figure 21. Pesticide use in Soybean Production 1964-1995.

Source:

Table 12. Herbicide Use in Soybean Production.

Herbicide/Crop	1964	1966	1971	1976	1982	1990	1991	1992
	Million Pounds active ingredient or acres							
Soybean								
Acifluorfen (N)[1]						1.1	0.9	1.1
Alachlor (A, SR)			6.3	29.6	30.9	14.7	12.8	10.2
Bentazon (A)				3.8	8.1	6.1	4.2	4.8
CDAA (AC)	0.9	1.0						
Chloramben (AC)	1.3	3.7	9.3	4.4	6.0	0.7	0.2	
Chlorimuron (N)						0.3	0.2	0.2
Clomazone (N)						2.7	1.9	1.4
Dinoseb (SR)				3.7	4.3			
Ethalfluralin (B, SR)						2.4	1.4	0.9
Glyphosate (A)						2.7	2.4	2.4
Imazaquin (N)						1.0	0.8	0.9
Imazethapyr (N)						0.4	0.7	0.9
Linuron (A, SR)		0.4	0.8	6.2	5.8	2.0	1.0	0.5
Metolachlor (A)					12.9	9.9	7.6	5.9
Metribuzin (A)				5.2	10.2	3.6	2.7	2.2
Naptalam (A)		0.9	3.0	3.9	4.4			
Pendimethalin (A)						6.8	7.9	9.7
Trifluralin (A, SR)	0.2	2.2	6.0	21.1	30.7	17.6	16.3	15.6
Other	1.8	2.2	11.1	3.2	11.9	2.4	1.9	2.1
Survey quantity	4.2	10.4	36.5	81.1	125.2	76.4	62.9	58.8
Surveyed acres	31.7	37.4	43.5	50.3	72.0	57.8	53.2	53.1
Percent acres treated	na	27	68	88	95	95	96	97
Lbs a.i./treated acre	na	1.03	1.23	1.83	1.83	1.33	1.23	1.14

[1]A: List A chemical in reregistration; AC: List A chemical not supported (canceled);
B: List B chemical in reregistration; BC: List B chemical not supported (canceled);
C: List C chemical in reregistration; CC: List C chemical not supported (canceled);
D: List D chemical in reregistration; DC: List D chemical not supported (canceled);
N: not in reregistration nor Special Review;
SR: the chemical either completed a Special Review or is in a Special Review.

na = not available.

Source: Lin, et. al., 1995, p. 14.

(d) Fuel and Machinery

Although we lack the comprehensive data on fuel and energy use on soybeans available for corn, it is fair to say that in the Corn Belt, many of the farms and much of the farm machinery accounted for in the analysis of corn above is also engaged in the production of soybeans. In this sense, the estimates for corn may be taken as including a substantial share of soybean production as well -- part of the corn-soybean complex. Put differently, to attribute fuel and machinery use separately to corn and soybeans would be to risk double counting.

(e) Per Acre Input Expenditures

In contrast to corn, the relative share of costs attributable to various inputs to soybean production show some important shifts, especially related to chemical costs, which have risen markedly since the mid-1980s relative to other inputs (Figures 22 and 23 and Appendix Table 7). In real terms, chemical costs have risen in constant 1992 dollars from 13.79 dollars in 1985 to 21.58 dollars in 1995. Energy costs have fallen in constant dollar terms, from a 1985 level of 12.49 dollars per acre to 8.68 dollars per acre in 1995. These figures suggest strong incentives to economize on the use of herbicides on soybeans, and the appeal of farming systems which reduce applications.

Figure 22. U.S. Soybean: Select Cash Costs (current year dollars).

Sources: "Revised Prices Received and Paid Indexes, United States, 1975-93; for Base Periods 1910-14=100 and 1990-92=100." Statistical Bulletin Number 917, National Agricultural Statistics Service, USDA, January 1995.

"Agricultural Prices," National Agricultural Statistics Service, USDA, March 1997.

"Farm Production Expenses," National Agricultural Statistics Service, USDA.

Figure 23. U.S. Soybean: Select Cash Costs (constant 1992 dollars).

Sources: "Revised Prices Received and Paid Indexes, United States, 1975-93; for Base Periods 1910-14=100 and 1990-92=100." Statistical Bulletin Number 917, National Agricultural Statistics Service, USDA, January 1995.

"Agricultural Prices," National Agricultural Statistics Service, USDA, March 1997.

"Farm Production Expenses," National Agricultural Statistics Service, USDA.

3. ***Cotton***

(a) Area Planted and Factors Affecting Yields

Cotton yields are measured after ginning (separating seeds from lint) in pounds or bales per acre. Cotton yields remained relatively flat from 1960 to 1980, but improved considerably in the 1980s (Figure 24). Again, 1994 was a record year for cotton yields at 708 pounds per acre. Trends over a 36 year period indicates an average yield increase of slightly more than 6 pounds of cotton lint per acre per year. Over the last 20 years, the trend is a doubling of yields. If the more recent period 1975-96 is taken separately, cotton yields have increased by 10.7 pounds per year compared with 6.27 pounds per year over the entire period 1960-1996. The trend line in the latter period fits as well as over the entire period, with an R^2 of .58 compared with .57 for the period as a whole.

Cotton, unlike corn and soybeans, is a Southern crop, with a different history and culture. In many respects, the land and labor constraints facing its early cultivation induced a different pattern of development from those described for corn and most soybeans. Cultivated throughout the Southern states East of the Mississippi in the late 18^{th} and throughout the 19^{th} centuries (when "Cotton was King"), it was a major export crop and the agricultural backbone (together with tobacco) of the antebellum and postbellum South. Because of its nutrient requirements, and the fact that many of the soils of the region were incapable of sustaining its production over time, it was subject to shifting cultivation as soils were depleted. Unlike the Upper Midwest, the labor constraints of the South were met first with slave labor, and after Emancipation with a continuing pool of low cost hand labor required for the time consuming tasks of weeding, insect control and harvesting cotton.

Figure 24. U.S. Cotton Yields 1960-96.

Source: USDA. Agricultural Statistics Board. National Agricultural Statistics Service. *Cotton and Wool Yearbook*. November 1996.

In the 20th century, the development of synthetic fibers, the increasing scarcity of labor due to Southern outmigration to Northern cities, and the general fall in cotton production after the drought and insect problems of the 1920s and 1930s led to a decline from 43.9 million cotton acres in 1925-29 to only 10.8 million acres in 1985-89. However, after 1989 cotton acreage rebounded, averaging 13.3 million acres since 1990, most of which has resulted from the expansion of acreage in the Southeast. The rather remarkable resurgence of cotton in the Southeast is attributable to several factors, including expanding global and domestic markets, near eradication of the boll weevil in several Southeastern states, and the development of short-season production systems that further reduced insect damages (Carlson, et. al., 1989; Cooke and Sundquist, 1991).

Cotton is grown in four distinctly different areas: the Southeast (Georgia, Alabama, North and South Carolina, Florida and Virginia); the Delta states (Mississippi, Arkansas, Louisiana, Tennessee, Missouri) where, like the Southeast, it is largely rainfed; the combination of dryland/irrigated cotton in the Texas High Plains and Rolling Plains of Oklahoma; and the strictly irrigation-dependent central Arizona and San Joaquin Valley of California. Here, we focus almost entirely on the 98 percent of U.S. cotton known as upland cotton (*Gossypium hirsutum*) as opposed to American Pima or extra long staple (ELS) cotton (*Gossypium barbadense*) grown in the irrigated West and parts of Texas.

As shown in Figure 25 and Appendix Table 8, since 1960, planted acres of cotton have been very uneven, falling from 16.5 million acres in 1961 to 9.4 million acres in 1967, rising again until 1974, falling in 1975 to 1961 levels, and tumbling precipitously from 1981 to 1983, when they reached a bottom from which they have climbed since, reaching a high of 16.9 million acres in 1995. Production has largely followed the same trend, but is affected by the differences in production on irrigated versus non-irrigated acres. In the irrigated West, for example, average yield in 1992 was 1,228 pounds per acre, compared with 700 pounds for the entire U.S. (Larson and Meyer, 1996). Acres planted but not harvested have remained at about one million over the period, with some increases in bad weather years in the 1980s and early 1990s. During the 1960s, 1970s and early 1980s, cotton acres lost out to soybeans, especially in the Southeast and Delta, a trend that was reversed in the late 1980s and 1990s as net returns to cotton grew relative to soybeans. Government programs also played a role, including a panoply of acreage allotments, marketing quotas and price supports in place between 1933 and 1965. In the 1970s, historical allotments were eliminated, although acreage reduction programs (ARPs) reduced output especially in years such as 1986, 1987 and 1989, when they were set at 25 percent of cotton base acres (Larson and Meyer, 1996, p. 17).

Overall, cotton has been buffeted by these and other forces, making the combination of tillage methods, weather, farm program rules, new varieties, as well as input use, especially difficult to disentangle. In a recent study of the role of weather versus management factors explaining cotton yields on the Southern High Plains (Miller, et. al., 1996), yields were analyzed for the period 1968-92. Multiple regression analysis suggested that dryland cotton yield was most strongly positively influenced by winter rainfall and negatively by the number of hot days. Weather influences in total accounted for about half of the variation in yields, with the remainder attributed to management.

Figure 25. U.S. Cotton: Acreage and Production 1960-96.

Source:

(b) Fertilizer Use

Fertilizer is used on most cotton acres, especially nitrogen, making cotton second only to corn in per acre fertilizer expenditures among the major field crops. Nitrogen was applied to 87 percent of cotton fields in 1995. Overall, expenditures for fertilizers on cotton in the U.S. as a whole averaged 35.62 dollars per acre in 1991, compared with 44.59 dollars for corn and 9.34 dollars for soybeans (Hyberg, 1996, p. 102). Phosphate was applied to 56 percent of planted acres, while potash was applied to 40 percent. Over the period from 1964 to 1995, nitrogen use on cotton fields has trended upward, from 75-80 percent of fields to 80-85 percent, while phosphate and potash have been applied to about the same percentage of fields (Figure 26). The rate of nitrogen application in pounds per acre stayed relatively constant at around 80 pounds until the 1990s, when it increased to 110 pounds in 1994 and then fell to 95 pounds in 1995 (Figure 27). Potash and phosphate use were also relatively constant, declining somewhat for phosphate from 60 to 50 pounds per acre over the period, and remaining in the 50-60 pound range for potash with a few exceptions. Total fertilizer use on cotton in billions of pounds reflects the rising use of nitrogen relative to phosphate and potash, with nitrogen use rising over the period, especially from a low of 437 million pounds in 1983 to the high of 1.4 billion pounds in 1995. 1983 was also the low year for potash and phosphate use, with phosphate use rising from 157 million pounds in that year to 408 million pounds in 1995, and total potash use rising from 124 million pounds to 745 million pounds from 1983-95 (Figure 28 and Appendix Table 9).

There is evidence that fertilizer applications on cotton may reflect very imprecise estimates of nutrient requirements due to inadequate soil testing. Baker, et. al., (1992) report cases in which reduced nitrogen applications were actually associated with ***increases*** in yields, due to excessive stalk growth and the decay of lower bolls (Hyberg, 1996).

In a study of irrigated and rainfed cotton in which row spacing, nitrogen application rates and population densities were studied in Louisiana, row spacing interacted significantly with nitrogen, so that nitrogen use rose from 90 to 120 pounds per acre when row spaces were reduced from 40 to 30 inches (Boquet and Coco, 1996). This indicates the extent to which a change in one input or cultural practice can affect another. However, trends in the use of fertilizer and pesticides are, relatively speaking, fairly clear.

Figure 26. U.S. Cotton: Percent Acres Fertilizer Applied 1964-95.

Figure 27. U.S. Cotton: Fertilizer Application Rate 1964-95.

Figure 28. U.S. Cotton: Total Fertilizer Use 1964-95.

(c) Pesticide Use

There is little question that cotton is a major user of pesticides, especially considering the relatively small planted acreage (16 million acres in 1995) that cotton occupies relative to corn (71 million acres in 1995) and soybeans (62 million acres in 1995). Cotton growers used 84 million pounds of pesticides in 1995, compared with about 69 million pounds applied to soybeans and 202 million pounds applied to corn. These use rates reflect an upward trend that has continued since the late 1980s. Even so, total use has not achieved the high levels of 1971, when 111 million pounds were applied (Figure 29). When broken into categories, herbicides were applied to 97 percent of cotton acres, and accounted for 33 million pounds of use in 1995. In the same year, about three quarters of planted acres received insecticide treatments, totaling 30 million pounds, and about 56 percent of planted acres received fungicide applications, equal to nearly 20 million pounds. These chemicals are a response to the large number of serious pests and diseases that attack cotton, especially seedling diseases, nematodes (parasitic worms) and weeds. In the hot and often humid areas where cotton is grown, weeds grow rapidly, including pigweed, sorghum and morning glory. Insect pests include boolworms/budworms, the boll weevil, and thrips and aphids.

Taken nationally, expenditures per acre for chemicals on cotton were the highest of all major field crops. Crutchfield, et. al. (1992) reported an average of 4.7 applications of insecticides, with nearly all cotton acres in the Southeast and Delta receiving at least one treatment of herbicides. Fungicides and defoliants were also commonly applied. Chemical pesticide expenditures were 48.19 dollars per acre for cotton in the U.S. as a whole in 1991, compared with 22.46 dollars per acre for corn and 22.51 dollars per acre for soybeans. In the

Delta, this figure rose to 89.89 dollars per acre for chemicals, compared with 70.27 dollars per acre in the Southeast, 19.69 dollars per acre in the Southern Plains and 50.05 dollars per acre in the Southwest (USDA, 1993).

Despite these aggressive pesticide measures, cotton losses to pests are very high. Blasingame (1992), Head (1992), and Byrd (1992) estimated that in 1992, 9 percent of cotton yields were lost to disease, 5.5 percent to insects and 7.7 percent to weeds. In the case of insects alone, losses equaled 33.39 dollars per acre, still less than the cost of chemicals applied in all regions but the Southern plains. Hence, reducing insect losses in cotton can have major implications for the bottom line at the farm level.

Figure 29. Pesticide Use in Cotton Production 1964-1995.

Sources:

(1) USDA. ERS. Natural Resources and Environment Division. "Pesticide and Fertilizer Use and Trends in U.S. Agriculture." *AREI Updates*. Agricultural Economic Report No. 717. May 1995.

(2) Ohio Agricultural Research and Development Center. "Pesticide Use on Major Crops in the North Central Region, 1978." Research Bulletin 1132. July 1981.

(3) USDA. ERS. Natural Resource Economics Division. "Pesticide Use on Selected Crops, Aggregated Data, 1977-80." Agriculture Information Bulletin No. 494. June 1985.

(4) Swanson, Jeffrey A. and Dale C. Dahl. *The U.S. Pesticide Industry: Usage Trends and Market Development*. Staff Paper Series P89-5. Department of Agricultural and Applied Economics. University of Minnesota. January 1989.

(5) USDA. ERS. National Agricultural Statistics Service and Economic Research Service. *Agricultural Chemical Usage 1995 Field Crops Summary*. March 1996. (Also year 1991, 1992, 1993 and 1994). (Adjusted for total crop acreage.)

(d) Fuel and Energy Use

Data on direct fuel and energy use in cotton production are scarce, although the indirect use of high levels of nitrogen fertilizer and pesticides clearly makes it an energy intensive crop. Moreover, most of the pesticide applications, especially in the Delta, are applied by airplanes.

(e) Per Acre Input Expenditures

Cotton input costs illustrate the difference between nominal and real expenditures (Figures 30 and 31 and Appendix Table 10). Chemical costs have been stable since the mid-1980s, but in constant 1992 dollars, costs for chemicals have fallen from 58.44 dollars per acre in 1985 to 43.85 dollars per acre in 1995. Consistent with the analysis above, these costs, despite their decline, remain the single largest expense item for cotton, followed by fertilizer, which has risen in constant 1992 dollars from 26.34 dollars per acre in 1987 to 38.37 dollars per acre in 1995. Energy costs have been variable in real terms while seed costs have trended upward, from a low of 6.70 dollars per acre in 1986 to 14.25 dollars per acre in 1995.

Figure 30. U.S. Cotton: Select Cash Costs (current year dollars).

Sources: "Revised Prices Received and Paid Indexes, United States, 1975-93; for Base Periods 1910-14=100 and 1990-92=100." Statistical Bulletin Number 917, National Agricultural Statistics Service, USDA, January 1995.

"Agricultural Prices," National Agricultural Statistics Service, USDA, March 1997.

"Farm Production Expenses," National Agricultural Statistics Service, USDA.

Figure 31. U.S. Cotton: Select Cash Costs (constant 1992 dollars).

Sources: "Revised Prices Received and Paid Indexes, United States, 1975-93; for Base Periods 1910-14=100 and 1990-92=100." Statistical Bulletin Number 917, National Agricultural Statistics Service, USDA, January 1995.

"Agricultural Prices," National Agricultural Statistics Service, USDA, March 1997.

"Farm Production Expenses," National Agricultural Statistics Service, USDA.

D. Tillage Practices and "Precision Farming Methods"

Two of the most important developments in agricultural technologies in the last decade have been the increasingly wide use of conservation tillage systems that reduce the use of certain inputs, and farming methods that apply these inputs with higher precision. These developments are important both to the cost structure of individual farm operations, and to the potential environmental impacts of input use, especially if conservation and protection of soil and water resources can be improved.

1. ***Conservation Tillage***

Conservation tillage may be considered part of an overall approach to crop residue management (CRM), including no-till, ridge till and mulch till, all conservation practices that provide sufficient residue in and on the soil to protect the soil surface from wind and water erosion. CRM usually involves fewer passes across the field with tillage implements, saving on machinery and fuel, although new investments in more specialized equipment may be required. The U.S. Department of Agriculture (USDA, 1994, p. 119) defines conservation tillage as any tillage and planting system that retains 30 percent of the soil surface covered by residue after planting and/or (in the case of wind erosion) maintains at least 1,000 pounds per acre of grain residue equivalent during windy periods. A conservation tillage system may take three forms:

- *Mulch till* -- in which the soil is disturbed prior to planting with chisels, field cultivators, disks, sweeps or blades.
- *Ridge till* -- in which the soil is left undisturbed from harvest to planting except for nutrient injection. Planting is into ridges with sweeps, disk openers, coulters or row cleaners and residue is left on the surface between ridges.

- *No-till* -- in which the soil is left undisturbed from harvest to planting except for nutrient injection. Planting is in a narrow seedbed or slot created by coulters, row cleaners, disk openers, inrow chisels or roto-tillers.

These tillage systems are in contrast to conventional systems using a moldboard plow and/or those that leave less than 30 percent of residue.

Conservation tillage systems have been adopted largely because, in addition to conserving soil and water, they are cost-effective. Fuel and labor savings, reduced depreciation of equipment, less soil compaction and higher soil fertility and structure are all economic benefits of these technologies. In addition, soil nutrients may be better retained, requiring less fertilization. Despite the advantages of no-till to corn production, certain soils, especially those that are not well-drained, may show decreased yields on no till fields (Stecker, et. al., 1995). An important issue has also been the use of herbicides, since weed growth may occur in untilled fields. The 1988-93 USDA Cropping Practices Surveys indicated that as of 1994, one of the three conservation tillage systems was used on 42 percent of corn acres in 1993, up from 21 percent in 1988, with mulch till the most common form of tillage (Figure 32). In Northern soybeans, conservation tillage has increased even more rapidly than for corn, up to nearly 50 percent in 1993, compared to less than 20 percent in 1989 (Figure 33). In Southern soybeans, as of 1992, adoption rates of conservation tillage were much lower (Figure 34). On cotton, almost all land was still in conventional tillage in 1993, although use of the moldboard plow fell to nearly half its 1989 levels (Figure 35). These data, together with data for wheat, are summarized in Table 13.

When these tillage systems are evaluated on lands designated as highly erodible, the growth of conservation tillage for corn and soybeans was 10 percent or more higher on HEL (highly erodible land) than on lands designated as non-highly erodible. In cotton, by contrast, there has been little increase in conservation tillage irrespective of erodible land type (USDA, *AREI Updates* #6, 1995). This finding in the case of cotton is significant, since it is estimated that despite reductions in cropland erosion, many highly erodible cotton acres remain (Hyberg, 1996).

One of the key elements of the regional analysis of on-farm use of Bt corn, Roundup-Ready soybeans and Bt cotton in Section II of this report will be the relationship between these crops and conservation tillage systems. If these crops are more compatible with and complementary to such systems, they may assist in reducing costs of production while advancing associated environmental benefits.

Micro-level analysis of the impacts of different tillage systems on machine costs, draft, insecticides, herbicides, nitrogen, phosphorus and potassium has been performed for corn and soybean production in Minnesota (Moncrief, et. al., 1987). These studies show that costs are clearly affected by tillage system, most particularly use of herbicides which decline for ridge till and rise for no-till. Rotations are also important, with the lowest input costs for soybeans after corn, followed by corn after soybeans, and highest for continuous corn.

Figure 32. Corn Tillage Systems, 1989-93.

Source: USDA, December 1994, p. 123.

Table 13. Tillage Systems Used in Field Crop Production in Major Producing States, 1988-93.[1]

Source: USDA, December 1994, p. 122.

Figure 33. Northern Soybean Tillage Systems, 1989-93.

Source: USDA, December 1994, p. 123.

Figure 34. Southern Soybean Tillage Systems, 1989-92.

Source: USDA, December 1994, p. 123.

Figure 35. Cotton Tillage Systems, 1989-93.

Source: USDA, December 1994, p. 124.

2. ***Precision Farming Methods***

New developments combining computers, satellites, soil sampling and testing, soil survey information, and field application equipment continue to be researched and marketed. Soil survey information is now digitized and specific farms or fields can be displayed on computer screens, identifying soil areas sensitive to erosion, leaching, water ponding or physical and chemical characteristics. Soil survey data can be combined with soil test information in on-board computers in fertilizer-herbicide applicator equipment, so that rates and combinations can be varied while moving across fields. Such site specific recommendations and applications will increase using the "farming by soils" or "farming by the foot" approach (Munson and Runge, 1990).

This increased use of highly specific crop management tailored to variability in soil type, topography, climate and cropping rotations is emerging rapidly as a frontier in agricultural technology. The increased use of digitized information systems, hooked to computerized applicators, planting and tillage equipment, has made it possible to vary the application of inputs so as to minimize costs, maintain or increase yields while conserving on inputs the excess application of which may cause leaching, runoff and consequent environmental damages (see USDA, 1994; Robert, et. al. [eds.], 1996). While the number of issues (and unknowns) involved in precision agriculture is quite large, the most important implication for new crop varieties such as Bt corn, Roundup-Ready soybeans and Bt cotton is that these seed types may also benefit, from the point of view of both production costs and environmental impacts, from an integrated system of precise input applications.

E. Summary and Conclusions

The interaction of technological and institutional change in American agriculture has produced a complex pattern of innovation with a striking result: steady increases in agricultural productivity over time. Numerous forces help to explain these developments.

First, the U.S. is endowed with a large area of highly fertile and well-watered cropland, supported by an educational and research infrastructure in its land grant colleges and private sector that produce some of the most technologically advanced agricultural methods in the world. The agricultural industry is tied to a huge complex of fertilizer, chemical, farm machinery and seed producing companies that make inputs available on a timely and cost-effective basis. Despite criticisms of the environmental impacts of high levels of these inputs, they have clearly been a critical underpinning of growth in productivity. The seed input, which will be a primary focus of subsequent analysis, offers new opportunities to substitute genetic information for some other of these inputs, economizing on their use and potentially reducing some of their environmental impacts.

A second main point is that American agriculture has used different and changing combinations of various inputs over time, from early reliance on mechanical substitutes for labor to later emphasis on hybrid seeds, fertilizer, chemicals and recent innovations in tillage and computer applications known as "precision agriculture." This flexibility and substitution belie simple analysis of the share of productivity gains attributed to single inputs, but suggest optimism over the possibility that new agricultural systems, based on information contained in the genes of corn, soybeans and cotton, combined with technologies leading to new and more precise tillage and input applications, are well within reach.

With respect to individual commodities, corn is perhaps the most well-documented. Yield increases have been marked, although the rate of increase has declined in the 1975-95 period. A major part of the explanation for increases in yields have been hybrid seed and genetic gains, which have in turn allowed more efficient use of farm harvesting machinery. Total fertilizer use began to decline after the early 1980s, and its more precise application was matched by growing effectiveness of pesticides applied to corn. Energy use on corn has been substantial, but less than indicated by some earlier analysis. Fuel use has changed from primary reliance on gasoline to diesel fuel, and fuel as a component of costs has become less significant relative to fertilizer and chemicals over time.

In soybeans, yield increases have also been steady, and have actually accelerated slightly in the 1975-95 period, although this period has been marked by greater instability in yields for both soybeans and corn. Genetic improvements in soybeans were minor until the 1980s and 1990s, when improvements in seed and genetics began an increase. Fertilizer use on soybeans is modest compared to corn, but herbicide is a major and significant input. Numerous new herbicides have improved cultural practices on soybeans and appear to be significant in explaining higher yields, but their costs create major incentives to economize on herbicide use. Fuel and machinery used on soybeans is closely connected to that used on corn, since the two crops are so often grown in rotation and combination. It is thus more useful to examine total fuel use patterns than to attempt to divide corn from soybean uses.

Cotton yields were relatively flat from 1960 to 1980, but improved considerably in the 1980s, reaching a record in 1994, the same year in which corn and soybeans also achieved record yields. Cotton acreage has been buffeted by changing demand side factors, government programs, and a variety of other factors. Fertilizer use has trended upward, especially nitrogen, as the Southeast has regained a major role in production. Cotton is heavily dependent on pesticides, especially insecticides, due to its vulnerability to a variety of pests, creating major incentives for the development of pest-reducing technologies, including Bt cotton. Fuel use on cotton is poorly documented.

A final set of observations returns to the emphasis on farming as a ***system***. Tillage methods have rapidly evolved, especially on corn and soybeans, that allow better protection of soil and water resources, although some increasing reliance on herbicides. These tillage methods appear highly compatible with genetically engineered crop varieties such as Round-up Ready soybeans. At the some time, more precise application methods for fertilizers and chemicals promise to reduce their application rates and to conserve on fuel and energy inputs. These systematic changes in agricultural technology hold out the promise of reducing overall input applications and costs, while maintaining and possibly even augmenting yields. As part of this system, genetically engineered crop varieties, including Bt corn and cotton and Round-up Ready soybeans, appear to fit well. How well they fit, and what particular environmental effects they may help to induce, will be considered in Part II of this study.

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APPENDIX*

Appendix Table 1. On-Farm Energy Use 1974-95.

*Source for all Appendix tables: USDA. ERS. National Resources and Environment Division. "Farm Fuel and Ethanol." *AREI Updates*. Number 16; December 1996.

Appendix Table 2. U.S. Corn: Yield, Acreage, and Total Production 1951-95.

Appendix Table 3. U.S. Corn: Fertilizer Use 1964-95.

Appendix Table 4. U.S. Corn: Select Cash Costs - *nominal and real dollars per acre*.

Appendix Table 5. U.S. Soybean: Yield, Acreage, and Total Production 1955-96.

Appendix Table 6. U.S. Soybean: Fertilizer Use 1964-95.

Appendix Table 7. U.S. Soybean: Select Cash Costs - *nominal and real dollars per acre*.

Appendix Table 8. U.S. Cotton: Yield, Acreage, and Total Production 1960-96.

Appendix Table 9. U.S. Cotton: Fertilizer Use 1964-95.

Appendix Table 10. U.S. Cotton: Select Cash Costs - *nominal and real dollars per acre*.