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CHAPTER 11

Science and Technology

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California agriculture today is known around the world for its diverse product mix, remarkable productivity, and technological sophistication. It is also known for its large-scale farm firms, vertical coordination in food marketing and processing, and, less happily, its environmental problems and farm-labor concerns. The development and adoption of improved technology has been a central element in all of the changes during the twentieth century that have led to the marvel that is today's California agriculture, and the problems that it faces in the twenty-first century. Technology is likely to be the solution to many of these new problems as well.

In this chapter we review the role of new technology in the development of California agriculture, emphasizing the period since World War II. First, we document the changes in the inputs and outputs over the 1949-91 period showing the general trend to save land and labor, to increase the use of capital and purchased inputs, and to increase the output of all categories, but especially vegetables, and nursery and greenhouse marketings. Along with the growth in measured productivity, there have been some important changes in the structure of agriculture as well as in the nature of farms and farming, with a trend to fewer and larger, more specialized farms being an important element of the structural change.

The second part of this chapter focuses on the evolution and adoption of various technologies in California agriculture. California is a part of the United States, and its agriculture has shared in many general developments such as the mechanical innovations that displaced the horse over the first half of this century, and other nationwide chemical and biological advances; still, California agriculture remains unlike farming in most of the rest of the country in many ways. We describe major changes in the elements of technology that have facilitated California's agricultural development, using examples of mechanical harvesters, pest-control strategies, and irrigation technology. We also discuss some examples of integrated systems involving multiple elements of production technology and marketing—such as the development of tomato varieties that could withstand mechanical harvesting, and the development of new strawberry varieties along with pest-control and production technology to match market requirements.

In the last part of the chapter we consider the sources of new agricultural technology and the role of government in providing resources for research and development, as well as institutional structures to facilitate private-sector activity.

TECHNOLOGICAL CHANGE AND CALIFORNIA AGRICULTURE

California agriculture today is very different from what it was in the gold rush years and through the early part of the twentieth century. In the early years, even in this century, there were few people to feed within California, and transportation costs and technology were such that perishable commodities were not economic to produce for shipment over long distances to the population centers in the East. The main focus of the state's agriculture was on producing grain under dryland conditions, either for human consumption or for livestock feed. Feeding horses was a primary role of California agriculture up through the 1920s. The development of irrigation, transportation infrastructure and technology, postharvest storage and handling technology and facilities, food preservation technology, and the growth of the state's population, along with the replacement of the horse by motorized vehicles, changed all that.

The seeds for the radical transformation of California agriculture during the twentieth century were sown in the last decades of the nineteenth century. In the first chapter of this volume, Olmstead and Rhode provide an overview of the history of California agriculture; they emphasize the role of technology.[1] We build on the foundation laid in that chapter. The key elements of technical change have included mechanization (including tillage technology, mechanical harvesters, bulk-handling, and transportation equipment), irrigation, agricultural chemicals (including fertilizers, pesticides, and hormones), improved varieties and other biological improvements, and improved management and information systems. These changes in technology have been made in conjunction with changes in the output and input mix, for related reasons.

[1] More detail on the role of different elements of new technology in the development of California agriculture in the late 1800s and early 1900s is provided in other publications. The process of mechanization, introducing labor-saving machinery, has been going on since the 1870s (e.g., as described by Olmstead and Rhode (1988) in relation to the grain industry). Other technologies affected the balance of products produced more than the input mix. For instance, Rhode (1990) emphasizes the role of capital accumulation and biological learning. Musoke and Olmstead (1982) explain California's relatively rapid, early, and extensive adoption of the mechanical cotton harvester in terms of the environmental conditions prevailing in California.

Important elements of change in California agriculture have included:

1. increases in demand for specialty products in eastern urban markets;
2. improved transportation, especially the transcontinental railroad; and
3. California's participation, along with the rest of the world, in the adoption of widely applicable mechanical technology and other general developments in agricultural technology, especially improved varieties and production practices.

To these we can add the effects of more-local factors, including:

4. the spread of irrigation;
5. the increased availability of "cheap" labor;
6. the importation of technology from other countries with similar climates, partly through immigrants bringing their knowledge and favored plant varieties; and
7. the accumulation of knowledge about California's environment and suitable agricultural production practices.

The ingredients and sources of change in the post-World War II period, which is the focus of the present chapter, can be seen to a great extent as a continuation of the process that began fifty to one hundred years earlier.

Inputs, Outputs, and Productivity Patterns, 1949-1991[2]

Indexes of output in California agriculture in the post-World War II era are shown in Table 1. In terms of total agricultural output, California farmers produced over three times as much in 1991 as in 1949 (the index went from 100 to 337).

Different components of agriculture grew at different rates at different times. For instance, greenhouse and nursery products grew almost tenfold (the index went from 100 to 977), while output of field crops (including wheat, rice, cotton, and corn) grew much more slowly (the index went from 100 to 266). There was considerable variation within individual categories, with some individual products growing very rapidly and others shrinking to negligible amounts. Thus the composition of California production changed markedly over the post-war period. Higher-valued products such as vegetables, greenhouse and nursery products, as well as fruits and nuts, account for a larger share of the value of agricultural output in the 1990s than they did in the immediate post-war period; the shares of livestock and field crops are smaller, accordingly, even though all sectors of California agriculture grew significantly over the period.

The use of inputs in California agriculture also changed markedly over the post-war period, as seen in Table 2. California agriculture's use of purchased inputs (e.g., electricity, feed, fertilizer, fuels and oil, and seed) more than trebled from 1949 to 1991 (the index increased from 100 to 355). The use of capital services—including physical inputs such as automobiles, tractors, trucks and combines, as well as biological inputs

[2] Craig and Pardey (1996) developed improved measures of indexes of agricultural outputs, inputs, and productivity based on the USDA's state-level data series. The figures in the text were taken from Acquaye, Alston, and Pardey (2003), who revised the Craig and Pardey data. The measures of inputs and outputs are quantity indexes (and therefore *real* rather than monetary measures) and are adjusted for changes in the composition and quality of their components.

such as dairy cows, ewes, and breeder pigs—grew by over 75 percent from 1949 to 1991 (an increase from 100 to 176). However, quality-adjusted land and labor use in agriculture declined. Land use fell by 8 percent (the index went from 100 to 92), while labor use decreased by 10 percent (the index went from 100 to 90). Across all input categories, the index of input use increased by 58 percent, from 100 to 158.

Table 1. California Agricultural Output, 1949-91 (Indexes, 1949 = 100)

Year	Total Output	Field Crops	Fruits & Nuts	Livestock	Vegetables	Greenhouse & Nursery
1949	100	100	100	100	100	100
1950	102	93	100	106	109	106
1955	128	120	113	137	134	141
1960	148	158	108	161	146	196
1965	168	161	133	188	147	245
1970	183	168	133	208	176	278
1975	229	262	181	216	197	409
1980	272	302	234	245	221	607
1985	294	284	249	272	250	726
1990	333	278	249	336	305	962
1991	337	266	270	339	280	977

Source: Compiled by Alston and Zilberman using data provided by Acquaye, Alston, and Pardey (2003).

Table 2. Input Use in California Agriculture, 1949-91 (Indexes, 1949 = 100)

Year	Total Input	Land	Labor	Capital	Purchased Inputs
1949	100	100	100	100	100
1950	102	100	101	103	102
1955	108	100	88	129	130
1960	123	99	88	155	178
1965	128	97	77	188	208
1970	120	93	68	134	235
1975	126	96	83	123	229
1980	136	100	76	143	286
1985	134	94	71	170	271
1990	155	92	87	180	334
1991	158	92	90	176	355

Source: Compiled by Alston and Zilberman using data provided by Acquaye, Alston, and Pardey, 2003.

That the 237 percent increase in agricultural output was achieved with only a 58 percent increase in agricultural inputs is a reflection of the changing productivity of those inputs. Expressing *aggregate* output per unit of *aggregate* input provides a measure of productivity, as shown in Table 3. Productivity (the index of output divided by the index of inputs) in California agriculture doubled between 1949 and 1991 (from 100 to 213). This means that, if input use had been held constant at the 1949 quantities, using 1991 technology would have resulted in twice as much output as using 1949 technology. Alternatively, to produce the output in 1991 using 1949 technology would require using twice as many inputs as were actually used. In other words, more than half of 1991's agricultural output is directly attributable to improved technology; and less than half is attributable to conventional inputs.

Table 3. Productivity Patterns in California Agriculture, 1949-91. (Indexes, 1949 =100)

Year	Output	Input	Productivity	Productivity
	----------------------*California*---------------------			*U.S.*
1949	100	100	100	100
1950	102	102	100	98
1955	128	108	119	111
1960	148	123	120	121
1965	168	128	131	128
1970	183	120	153	143
1975	229	126	182	169
1980	272	136	200	181
1985	294	134	219	215
1990	333	155	215	220
1991	337	158	213	224

Source: Compiled by Alston and Zilberman using data in Tables 1 and 2.

Growth rates of output, input use, and productivity have varied widely from decade to decade. The period of greatest productivity growth was during the 1970s when global commodity markets boomed. The 1980s was a decade of relatively slow growth in output and productivity. Based on similar data ending in 1985, Alston, Pardey, and Carter (1994) estimated that the rate of return to public-sector agricultural R&D in California, to which much of that productivity growth could be attributed, was around 20 percent per annum in real (inflation-adjusted) terms.[3]

Complete, specific data on inputs, outputs, and productivity in California and U.S. agriculture, comparable to those in Tables 1 through 3, are not yet available for the years after 1991. However, the data that are available suggest that the 1990s reflected a

[3] This estimate is lower than the estimates obtained in most studies of rates of return to agricultural research, which are more often in the range of 40 to 60 percent per annum (see Alston, Chan-Kang, Marra, Pardey, and Wyatt, 2000, for a critical review of this literature, and a meta-analysis of the estimates). Partly that is because Alston, Pardey, and Carter (1994) used conservative assumptions, which tended to result in lower estimates. They also showed that their estimate was relatively robust in that a similar rate of return was obtained regardless of the treatment of extension expenditures or allowances for private R&D roles.

return to a more-normal rate of productivity growth in California, sustaining the longer-term average rate, in the range of 2 percent per annum. Mullen et al. (2003, pp. 16-19) applied California's 1949-1991 average annual agricultural productivity growth rate of 1.81 percent per year to the period 1949-1999. They found that with 1950s productivity and the actual inputs used, output in 1999 would have been only 42 percent of the actual value of $25.3 billion. Hence, the factors that gave rise to productivity growth since 1950 accounted for $14.8 billion worth of output in 1999 alone. Considering the period 1949-1999, Mullen et al. estimated that if public agricultural R&D accounted for one-sixth of the productivity growth (a conservative estimate) the benefit-cost ratio for public investments in agricultural R&D would still be 6:1 (a return of $6 for every $1 invested).

Changes in inputs, outputs, and productivity in California agriculture paralleled similar changes in other states and around the world, but with some important differences reflecting elements unique to California. As a result of these changes, farms and farming today are very different from what they were in the early part of the twentieth century. Clearly, new technology has been a major driver in the development of California agriculture—and not just agricultural technology. Important changes off the farm have included improvements in methods of food preservation, storage, transport, and handling, along with general improvements in the transportation infrastructure. A host of other technological changes have been applied on the farm. Many of these have been shared with agriculture in other places, and beyond agriculture. In what follows we emphasize those developments that have been specific to California and important here, focusing for the most part on technology applicable at the farm level.

EVOLUTION AND ADOPTION OF AGRICULTURAL TECHNOLOGIES IN CALIFORNIA

The process of technological innovation in California has much in common with the process of technological innovation in the United States more generally. Nonetheless, there are some unique features. Like other regions in the United States in the early part of the twentieth century, changes in technology in California emphasized the adoption of mechanical technology—improved plows, various kinds of harvesting machines that were initially powered by animal power or steam engines, tractors, and so on. All of these innovations reduced costs, especially labor per acre.[4] Such mechanical inventions enabled the establishment of land-intensive agriculture and, together with the Homestead Act of 1862, were crucial elements in the settlement of California.

As in the rest of the United States, California agricultural production in the twentieth century has grown primarily through increases in yield per acre. California farmers were early in their adoption of chemical inputs such as fertilizers and pesticides, and swiftly took up more advanced agronomic and biological management practices. Recently, California has become the leader in introducing biotechnology and computerized systems into agriculture.

[4] See Cochrane (1993); Hayami and Ruttan (1970); Olmstead and Rhode (1993).

Unlike other states, however, the growth of agriculture in California required diversion of water. From the nineteenth century on, California agriculture emphasized the introduction and adoption of institutions and technology to facilitate irrigated agriculture. The institutions ranged from local collective arrangements for diverting the water (water districts) to massive state water projects. Technology emphasized physical innovations in delivering water to improve control and efficiency. In California, as in other western states, much emphasis was given to improved irrigation technologies. California farmers used modern irrigation methods, such as sprinkler and drip, to introduce advances in the use of chemical fertilizers. More recently, computerization has contributed to the more precise management of irrigation.

While the emphasis on irrigation is one distinctive feature in California agriculture, perhaps an even more important feature that distinguishes this state is the selection of crops. California agriculture is the leading producer of fruits, nuts, vegetables, and flowers in the nation—and, for many fruit and nut crops, in the world. The land share of these crops has grown steadily over time. The nature of these crops, which are less important in much of the heartland of the United States, means that a great deal of the technological development in California has more in common with Florida, parts of the southern hemisphere, and regions of the Middle East (as well as with Italy, France, Israel, and even Holland), than with Illinois and Iowa.

The evolution of agricultural technology in California was strongly influenced by technological innovations and other events that originated in nonagricultural sectors of the economy. During the late nineteenth and early twentieth centuries, much of the Central Valley consisted predominantly of grain-producing areas. Grains were essential for feeding the local population and their draft animals, which provided the main source of energy for transportation and farming. Early California exported grain mostly by boat, but the introduction of the railroad provided a cheaper alternative. Dried or preserved fruits and vegetables were also shipped, since logistical constraints prevented the export of products with a relatively short shelf life. During the second half of the twentieth century, with the introduction of the federal highway system and great improvements in truck transportation, California began shifting toward the export of fresh fruits and vegetables. The past 10 or 20 years have seen increased airplane transportation to export high value-added, tree-ripened fruits from California to markets in Pacific Rim countries as well as along the East Coast—another step in the continuing process of supply response to improved transportation technology that began a century earlier (Rhode, 1990).

International Technology Spillovers

Subtropical crops and vegetables produced in California have had extensive technological exchange with other regions where weather and crops are similar. In the nineteenth century and early twentieth century, a significant transfer of technology came from southern Europe and Asia to California, embodied in the immigrants from Italy, Germany, France, Armenia, and Odessa near the Black Sea who settled in the San Joaquin Valley, near the Russian River, and in other areas of California. These immigrants brought crop varieties and cultivation practices from their original countries and established the foundation for many fruit and vegetable industries in California.

Traffic in ideas and technology has been on a two-way street, however. Early on, for example, the wine industry in California was essentially an importer of knowledge from France and Italy. However, as the University of California developed its significant research capacities, the state evolved from being an importer to an equal trader and even exporter of agricultural knowledge. California developed its own varieties of wine grapes, stone fruits, nuts, and citrus, and some California grape varieties were even sent to France to cope with a plethora of problems in the wine industry there.

While traditionally in many Mediterranean countries almond and other nut trees were grown mostly as single trees, without much cultivation, California researchers in the Experiment Station made a strong effort to adapt many nut varieties to California conditions and to increase their intensity of production. California has become the leading state worldwide for varieties as well as production methods in almonds, walnuts, and pistachios. Additionally, realizing the relatively small markets for many fruits and vegetables, California farmers have continually sought to produce new specialty crops and develop markets for them.

Transfers of technologies between California and regions with similar crops and growing conditions have continued. Drip irrigation and the production system developed around it came from Israel. Some South African entrepreneurs and Australian companies have played a major role in technology transfer.[5] California has been a major beneficiary of the Bi-National Agricultural Research and Development (BARD) program with Israel. This research program, with an endowment of about $200 million, has allocated a large share of its U.S. funds to California research institutes. Much of the expected economic benefit from this program (estimated in 1987 to be around $500 or $600 million) has accrued to growers in the form of improved irrigation and drainage practices, the use of computerized systems in cotton production, introduction of solarization for pest control, and so on.

California growers constantly benefit from varieties being developed in other countries, including high-value flower and vegetable crops from the Netherlands and, especially, the range of fruits and vegetables from Asia. The international spillovers of genetic material are not confined to exotic species, however. For instance, Pardey, Alston, Christian, and Fan (1996) showed that California has been a major beneficiary of new wheat and rice varieties developed by the International Agricultural Research Centers of the Consultative Group on International Agricultural Research (CGIAR). The new higher-yielding wheat varieties developed by the International Maize and Wheat Improvement Center (CIMMYT) in Mexico, incorporating semi-dwarfing genes and rust resistance, were designed for developing countries but turned out to be especially suitable for use either directly, or as parental lines, in California and Australia. Similarly, the improved rice varieties from the International Rice Research Institute (IRRI) in the Philippines have been relatively well suited for adaptation and adoption in California. Essentially all of California's rice has some IRRI ancestors.

[5] Tom Riddering, from South Africa, was crucial in the establishment of a large-scale drip irrigation company in California, Agrifim, and he has been a dominant force in California's irrigation industry. Hardy, an Australian company, became a major player in California irrigation. Much earlier, the Chaffey brothers from California pioneered the development of irrigation in the Murray Valley, leading to the development of the grape and citrus industries in the Sunraysia region of Australia.

Asian-Americans have played a dominant role in California's high-value crops, especially along the coast. While California has been a significant importer of crops and varieties, exports of crops and genetic material from California have outweighed the imports significantly. In the future, we may expect much more emphasis on the development of crops and varieties to meet Pacific Rim demands. California has by far the world's strongest research establishment in subtropical agriculture, exporting knowledge that was crucial in the development of cotton and subtropical farming in Australia, Israel, and other countries.[6]

In recent years a significant transfer of agricultural technology has taken place, including processing as well as production technologies, from Northern California to Latin America, especially Chile and Mexico. NAFTA may well encourage a gradual integration of farming in California and certain regions in Mexico that produce high-value crops. Finally, there has been a steady technology exchange between California and Florida, which are unique in the nation for their subtropical crops such as citrus.[7]

Irrigation Technology

Without irrigation, much of California would be a dry and nonproductive land. With irrigation, however, the Central Valley has become the most agriculturally productive valley in the world. Combined with the soils, climate, and a long growing season, water availability has brought high yields per acre for a multitude of crops.

Traditional irrigation in California was based on gravity and consisted of either flooding the fields or using furrow delivery. These methods were often technically inefficient, since a significant portion of applied water was not consumed by the crop but ended up as deep percolation, runoff, or evaporated water. Modern technology has increased irrigation efficiency significantly. Sprinkler and drip irrigation can increase yields and save water, especially in areas with sandy soils where deep percolation is significant, and with uneven soil topography where problems of runoff are severe. The problem with percolation is especially serious in some areas of the Central Valley where there is an impenetrable soil layer close to the surface, which results in water-logging problems. In these cases, adoption of modern irrigation methods can avoid or slow these problems.

While modern irrigation tends to increase revenue by increasing productivity, it can entail higher capital costs. Producers must balance gains against costs. Studies suggest that adoption of the new methods is most appropriate in areas with high-value crops, high prices of water, and farming conditions (sandy soils, deep hills) that make them attractive. Modern technologies are not appropriate for every location, as for example in areas with low-value crops (field crops such as wheat and barley) and heavy or poorly drained soils. At present, only 25 percent of California farmland is

[6] Cotton was introduced in Israel by a California farmer, Sam Hamburg, and the largest cotton grower in California, Boswell, was at one time probably the largest operation in Australia as well. Conversely, the Tatura trellis, developed in Tatura in Australia, has been adopted and adapted for use much more extensively in the fruit industries elsewhere in the world, especially South Africa, Israel, and California, than in Australia. These spillovers arise as a matter of course, since most mechanical, chemical, and biological technologies know no geopolitical boundaries and can be applied in many places with similar agroecologies.

[7] Alston (2002) reviewed the evidence on interstate and international technology spillovers. In most U.S. states, spillins from public research conducted in other countries and states may be as important as own-state public research investments as a source of new agricultural technologies. At the same time, spillouts of agricultural technologies from the United States have been very important for agriculture in other countries.

irrigated by sprinkler, and the share of drip is 10 percent or less. Table 4 presents information about adoption of irrigation technology over time in California.

Flood Irrigation. While sprinklers and drip delivery systems can cope with uneven terrain, much of California's irrigated agriculture is irrigated by flood or ditch-and-furrow methods fed by gravity, especially field crops (over 5 million acres, and still two-thirds of the irrigated area in 1994, as shown in Table 4). An important element in the development of irrigation technology for these crops, and improvement in the control of water, has been the use of improved grading techniques, especially *laser levelling* technology. Much Central Valley farmland has been leveled over the years, making flood and ditch-and-furrow irrigation efficient and cost-effective.

Table 4. Adoption of Irrigation Technology in California, 1969-1994

Year[a]	------Sprinkler------		-----Gravity[b]-----		--Drip or Trickle[c]--		Subirrigation	
	Farms	*Acres*	*Farms*	*Acres*	*Farms*	*Acres*	*Farms*	*Acres*
1969	12,708	1,261,494	34,322	5,970,451	--	--	525	91,153
1974	12,872	1,407,098	31,796	6,221,203	--	--	518	129,940
1978	25,056	2,135,959	35,056	6,351,354	3,922	191,549	145	30,765
1988	16,698	1,747,231	27,306	5,594,321	8,759	359,843	616	75,515
1994	20,366	1,848,697	24,046	5,185,677	14,019	933,696	85	55,896

a) These are census years.
b) Gravity in 1969 and 1974 is the sum of flood and ditch-and-furrow irrigation.
c) Data not available for 1969 and 1974.
Source: Census of Agriculture, U.S. Department of Commerce.

Irrigated agriculture in California benefited from developments outside agriculture and from the importation of technologies from outside the United States. The ability to drill deep wells and convey water under high pressure, activities important to the use of sprinkler systems, came in large part from knowledge acquired in the oil industry; learning how to pump and transfer liquid in the oil business led to developments later found to be profitable when applied to water.[8]

Sprinkler Irrigation. While sprinkler irrigation was introduced prior to World War II, the sprinkler manufacturing industry went through a period of rapid expansion after the war. The early sprinkler systems consisted of iron pipes that connected sprinklers to the main water line. The early post-war years also saw an excess U.S. production capacity for aluminum; since then, there has been a rapid increase in the share of irrigation systems that use lighter aluminum pipes, which have enabled the introduction of movable sprinkler systems at lower cost, an attractive alternative for

[8] This observation is credited to the late Yair Guron.

some field crops, including cotton. Sprinkler systems were largely promoted by manufacturers and dealers from which farmers rented equipment in early years. As they became more knowledgeable about sprinkler irrigation, farmers rented equipment less frequently and began to purchase it outright.

Sprinkler irrigation has been adopted for a wide variety of crops. Since different crops have different requirements, and the profitability of investment in equipment may be different, various types of sprinkler systems have evolved; this evolution also reflects new opportunities with respect to materials and equipment. Many field crops still use the removable sprinkler system. In these cases, farms do not spend much money on equipment; the pipes are simply moved from field to field, which restricts the frequency of irrigation. Higher value crops use permanent sprinkler systems, which allow quicker response to changes in weather and also permit longer irrigation cycles with lower volumes, which increases water use efficiency. In some cases, sprinkler systems are also used for frost protection. With the introduction of plastic, there has been a demand for sprinkler systems relying on plastic pipes and meters, which may be less expensive in terms of cost and easier to move, but may require more frequent replacement.

Center Pivot. The most significant adaptation of the sprinkler system was the introduction of center pivot irrigation in the 1970s. This system revolutionized agriculture in the Midwest and increased the irrigated acres in the United States by several million acres, but it has not had a significant impact on California agriculture. Center pivot irrigation is most appropriate for crops such as corn, and is most efficient when the same machinery is used for both pumping of groundwater and irrigation. This system also requires production in continuous plots of quarter sections (160 acres). While center pivot might have been appropriate for crops such as alfalfa and cotton in California, reliance on groundwater for these crops is not very common, so a combination of pumping and irrigation is not likely.

Drip Irrigation. Drip irrigation is another form of modern irrigation that has had significant impact on California agriculture. Introduced into California in the late 1960s, drip was initially exported from Israel. This system requires a high up-front investment; therefore, it is primarily adopted for high-value crops in situations of water scarcity, and in locations where it is especially favorable. The first significant adoption of drip was in the avocado orchards of the San Diego area, where it enabled expansion to steeper hills in both San Diego and Ventura Counties. Similarly, the use of drip enabled expansion of grape production to the hills of Monterey County and throughout the Central Valley.

Drip systems can be very complex. During the early 1980s, the adoption of drip expanded, and local dealers and personnel developed the skills to design and improve the systems. Currently, much of the design is done at the dealer level, and dealerships often have sales engineers who can design sophisticated drip systems. Some large farms are able to design their own systems with the help of professional designers. Advantages associated with the introduction of drip in high-value crops in California are reduction of chemical use and replacement of unskilled laborers with a smaller number of more highly skilled employees.

Continuous processes of adaptation and improvement of the technology reduced the fixed cost of drip systems, and the effectiveness of use increased because of "learning-by-using" by farmers. Some farmers combine drip with computer technology to allow irrigation activities to respond to environmental conditions. This version of precision agriculture has been found in some areas to increase yield and reduce water use significantly (Parker et al., 1996). In the future, the combination of drip and sprinkler irrigation with automated computerized systems that use weather and other data to adjust timing and flow will almost certainly become more popular.

Information Technology. Public investment in provision of weather information in the form of the California Irrigation Management Information System (CIMIS) has given impetus to the development of computerized and automated irrigation systems. About 100 weather stations have been established throughout the state to provide detailed weather information via telephone, e-mail, and other modes of communication. Water districts, irrigation consultants, and growers have gradually joined the CIMIS system (Parker et al., 1996), and the annual benefits are estimated at about 20 times its cost. The introduction of this public weather system has reduced the cost of information to farmers and resulted in a proliferation of consultants who use the data, develop software, and provide farmers with irrigation advice. These consultants have gradually changed the way California agriculture operates. CIMIS has also provided a means to increase productivity and incomes; in the future the use of consultants, computers, weather stations, and more precise irrigation is likely to expand beyond the regions and the crops in which they are currently used.

Water Markets. The California experience suggests that immense benefits are associated with the provision of knowledge that enables the introduction and improvement of technologies. Public policies that support provision of infrastructure (such as CIMIS) and favorable economic conditions are crucial for technological development. However, policies involving the transfer of water in the past were not particularly conducive to increased irrigation efficiency. Water markets (i.e., trading in water) may offer an opportunity to transfer water away from agriculture; on the other hand, they may also provide a significant impetus for improving water use efficiency. As water markets develop in response to water scarcity, we may expect to see an increase in adoption of modern irrigation practices and more rapid development of new, improved practices.

Harvest Technologies

In many cases in the past, the expansion of crop acreage was slowed by labor availability and costs associated with harvesting. The complexity of fruit and vegetable crop harvesting, partly related to the fragility of the produce, has combined with relatively small markets for equipment to make the introduction of harvesting equipment slower for these crops than for some major field crops. For many fruit and vegetable crops, mechanical harvesters were not introduced or significantly adopted until the 1960s or 1970s, and a range of significant commodities (e.g., grapes for raisins and most fresh fruits and vegetables) continue to be harvested by hand because mechanical harvesting technology remains unavailable or costly.

Available data on the introduction and adoption of mechanical harvesters is sketchy and incomplete.[9] Relatively good information is available on the cotton harvester (e.g., Musoke and Olmstead, 1982) and the tomato harvester, which received particular attention from economists because it was controversial. University research has played a major role in developing harvesting technology for tomatoes, wine grapes, and lettuce. Economic considerations often delayed the introduction of such technologies once they were available, but also helped promote their adoption later.

Tomatoes. The processing tomato industry, in particular, was dependent on the Bracero Program, which was terminated in 1965. Introduced in the post-World War II period, the program contributed to the expansion of labor-intensive crops in California and to the transfer of production of major vegetable crops, especially tomatoes, from other states to California. That same year a mechanical tomato picker was introduced which coincided with the introduction of a new variety suited for mechanical harvesting. The design for the tomato harvester was devised by a private company (Blackwelder), based on a design developed at the University of California at Davis. The machines worked better with new varieties of processing tomatoes bred especially for mechanical handling, which were also developed by the University. Following the cancellation of the Bracero Program, adoption of the tomato harvester (and suitable new tomato varieties) was remarkably swift; by 1968, 95 percent of California's processing tomatoes were mechanically harvested (Zahara and Johnson, 1979). Not only was the technology beneficial to growers—reducing labor uncertainty and decreasing costs—it also improved the lot of consumers by reducing the cost of tomato products.

Critics charged, however, that the introduction of the tomato harvester negatively affected farm workers (Schmitz and Seckler, 1970). The case is not altogether clear. California's processing tomato industry today employs many more workers than it did when the tomato harvester was first introduced. If the harvester were banned, the California processing tomato industry would be so adversely affected that the effects on workers would be clearly negative. Such longer-term consequences of the introduction of so-called labor-saving technology have not always been fully appreciated. The total impact on farm workers of harvest mechanization depends on both the effect on labor intensity (negative), and the effect on the scale of production (positive).[10]

Lettuce. The introduction of the mechanical lettuce harvester seemed also to be a response to labor-supply problems. With the advent of the lettuce harvester, however, labor demand in both harvesting and postharvest activities declined. On the other

[9] Zahara and Johnson (1979) reported figures for the United States as a whole: at that time, for processing uses, 38 percent of fruits and 58 percent of vegetables were machine harvested; for the fresh market, over 90 percent of the nuts, 26 percent of the vegetables, and less than 1 percent of the fruits were mechanically harvested. Their article provides detail on some specific California crops.

[10] Martin and Olmstead (1985) provide an excellent discussion of the tomato harvester issue and the agricultural mechanization controversy more generally, including a discussion of the implications of mechanization for consumers, food quality, rural life and rural communities, as well as for employment.

hand, productivity increased significantly. Because owners needed more commitment and responsibility from workers, they began contracting with unions, and contracts brought workers higher pay and longer employment, although in many fewer jobs.

In the year following the Bracero Program, illegal immigration of farm workers to California increased. The transaction costs associated with recruitment of seasonal labor during the Bracero Program and especially afterwards stimulated the use of farm labor contractors (FLC), who take responsibility for the recruitment of laborers. The adoption of FLCs was further stimulated by the introduction of the Immigration Reform and Control Act of 1986 (IRCA), which was intended to reduce the flow of illegal immigrants and has changed the risk to farmers of employing potential illegals directly.[11] Although the literature raises doubts about the effectiveness of the changing regulations in controlling the flow of immigrants, the rules have affected the nature and reliability of the agricultural labor force as well as the costs of labor. Such factors are likely to continue to be an incentive for farmers to seek labor-saving alternatives.

Cotton. Harvesting technology has played a major role in the California cotton industry, as documented by Musoke and Olmstead (1982). California's cotton industry expanded rapidly in the immediate post-World War II years, with the adoption of mechanical harvesting being a major reason. California cotton growers adopted mechanical harvesters more rapidly and more completely than farmers in other states. Musoke and Olmstead attribute this rapid adoption to factors such as the relatively large size of California farms and dry weather during the harvest season, factors that may also have contributed to California's relatively rapid adoption of other mechanical technologies. By 1960, over 90 percent of California's cotton was mechanically harvested; by 1965, virtually 100 percent.

Fruits, Nuts, and Vegetables. Mechanical harvesting and bulk handling equipment have been important innovations in California's horticultural industries. In many fruit and vegetable industries, especially those where products were destined for processing, harvesting innovations came in the 1960s or earlier and became standard technology by the 1970s. For instance, Zahara and Johnson (1979) reported 100 percent mechanical harvesting in 1978 for a variety of processing vegetables, including snap beans, carrots, sweet corn, onions, green peas, and potatoes. However, none of the fresh or processing fruits used significant mechanical harvesting except prunes and dates (100 percent mechanically harvested) and tart cherries (75 percent). In fresh vegetables, mechanical harvesting was important only for carrots and potatoes. Mechanical harvesters for wine grapes were introduced in California in the late 1960s, and by 1974 between 5 and 10 percent of the crush was mechanically harvested (Johnson 1977); by 1978, 20 percent (Zahara and Johnson 1979). Currently, perhaps half of the crush is mechanically harvested.[12] On the other hand, by 1975 virtually all almonds, pecans, filberts, and walnuts were mechanically harvested; mostly produced in California.

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[11] Much has been written about this topic, including articles by Taylor and Thilmany (1992, 1993), Thilmany (1996), Thilmany and Blank (1996), and Thilmany and Martin (1995).
[12] Personal communication, Pete Christensen.

Genetic Improvement

Genetic improvement has led to higher-yielding varieties, with improved pest resistance, as well as varieties that have other advantages such as improved quality, suitability for particular growing areas, or different seasons.

Wheat and Rice. As discussed above, California has benefited from the adoption and adaptation of new wheat and rice varieties developed in the CGIAR. California's role has been to develop varieties with local adaptation from the parental material developed by the international centers. California's wheat and rice yields have improved substantially as a result of this synergistic, multinational effort.

Almonds. Other examples of genetic improvement have been entirely the result of local efforts. California's almond yields per acre roughly tripled between 1950 and 1990, as a result of a combination of improved varieties that allow higher planting densities, and other improvements in technology.[13] Other cost-saving improvements, such as improved irrigation methods and mechanical harvesting, and overall quality enhancement have helped spur the growth of the almond industry in California to the point where it now dominates the world market. Similar developments in technology and management have been an important impetus in many of California's other "Cinderella" industries, including other nuts, fruits, and vegetables.

Grapes. Yield improvement is not the only form of varietal improvement. In several industries, varietal improvement has brought improvements in quality, though sometimes at the expense of yield, or an increase in the number of varieties available, which offers more choice for consumers or an extension of the season for short-season fruits. Table grapes are a good example. In 1953 there were only three important table grape varieties (Thompson Seedless being the most important for fresh as well as drying use, and perhaps white wine). By 1993, eight specific table-grape varieties were planted on over 2,000 acres each; several of these are superior quality seedless varieties. The extension of the season and the range of varieties are thought to have provided an important stimulus to demand for fresh grapes.[14]

California's grape industry has been devastated in the past by pests, such as Phylloxera, and is currently threatened by Pierce's Disease, transmitted by the Glassy-Winged Sharpshooter. The use of resistant rootstocks, a form of genetic improvement, was the solution for Phylloxera, and genetic resistance (perhaps through biotechnology) is seen by many as the long-term solution for Pierce's disease as well.

Strawberries. A similar story holds with California strawberries. In this case the variety improvements extended a short season to almost year-round availability of high quality fruit, at the same time bringing huge yield gains. Genetic improvements were only a part of the strawberry miracle, which combined advances in pest control with better general management.[15]

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[13] See Alston, Carman, Christian, Dorfman, Murua, and Sexton (1995) for details.
[14] See Alston, Chalfant, Christian, Meng, and Piggott (1997).
[15] See Alston, Pardey, and Carter (1994) for an extended discussion.

Lettuce. Another example of multifaceted varietal improvement is provided by the California lettuce industry. At one time, lettuce meant only iceberg lettuce. Today California grows many distinct types and varieties of lettuce, so that the U.S. salad bar can be stocked year-round with a range of fresh lettuce. Again, the combination of improved genetic material with other mechanical, chemical, biological, and postharvest technologies, along with a better understanding of the market, have resulted in a commercial success story.

Regulation of Cotton Varieties. Technological regulation is likely to become more important over time, as elements of society become more concerned about the consequences of today's production methods for issues such as food safety, environmental contamination, and animal welfare. Technological regulation attempts to exercise control over production methods so as to safeguard product quality, worker safety, animal welfare, and the environment.

Technological regulation may also allow one group of producers to profit at the expense of others—and perhaps at the expense of society as a whole. An important example of this has been the regulation of variety choices in the California cotton industry under a law introduced in 1925, which restricted production to a single variety of Acala cotton, supposedly to promote demand. Constantine, Alston, and Smith (1994) showed that the evidence of an important stimulus to demand is lacking, yet the one-variety law had a depressing effect on yield in some parts of the San Joaquin Valley while growers in other parts of the Valley benefited both from having suitable planting material for their conditions and a higher price for their cotton. Overall, the beneficiaries outnumbered the losers, and the law remained in force for over 50 years, until a 1978 amendment opened the industry to private breeders.

Biotechnology. Barriers to the development and adoption of new technologies include market, social, and other economic factors as well as regulatory constraints. Taken together, these aspects are presenting substantial barriers to the development and adoption of genetically engineered crop varieties, generally, and for California's specialty crops these barriers may preclude access to new varieties developed by genetic engineering. The same types of factors may leave many California crops as orphans with respect to conventional pest control technologies as well—for many such crops the market is too small and the research, regulatory, and other costs are too large to allow profitable development of new, specific pest-control technologies.

Pest Management

To a large extent, the ability of California farmers to grow more than 200 different crops stems from their ability to develop and apply technologies enabling plants to resist a multitude of diseases and pests that prevent them from being grown elsewhere. The relatively dry weather of the Central Valley reduces the severity of some pest problems that have plagued other, more humid regions growing similar crops. Nevertheless, without the extensive research, extension, and pest control application activities carried on throughout the state to combat plant diseases and pests, California's agriculture would not be nearly as diversified or successful as it is today.

The unique composition and diversity of California agriculture have challenged its agricultural research system. Farmers must find solutions to many pest and plant disease problems, and do not benefit much from spillover of research done elsewhere. The California Agricultural Experiment Station and Extension Service have developed major research programs in Entomology and Plant Pathology, and the Center for Disease Control has also played a major role. Furthermore, some private chemical companies have developed large research and experimentation facilities in California to address pest problems, especially in high-value crops. There has been significant collaboration between the public sector and private companies in working on pest control. Chemical companies have provided universities with various compounds to address emerging pest problems and relied on university facilities to test new materials and develop appropriate procedures for their use. A major challenge in pest control has been the development of effective procedures for the use of chemicals, and this has been an area of close collaboration between private and public sectors.

Chemical Pesticides. Chemical pesticides have been essential in controlling severe outbreaks of pests. The Experiment Station and the Extension Service have played important roles in identifying and disseminating chemical solutions to pest problems. For example, the identification and development of procedures for using methyl bromide to control fusarium and other soil-borne diseases in strawberries and other high-value crops was a major research accomplishment of the California Agricultural Experiment Station.

Zilberman, Siebert, and Schmitz (1990) document that chemical pest controls have had a wide range of impacts—increasing crop yields, reducing production costs, improving product quality, expanding shelf life of commodities, and reducing inventory losses. On the other hand, the productivity gains from use of pesticides have external costs. The high intensity of pesticide use in the high-value crops of California, and the high intensity of labor use, bring significant worker safety risks. Some chemicals, such as the DBCPs, which have significant productivity effects, have been discovered to be carcinogenic; there are worker safety and groundwater contamination problems. As discussed by Carter (2001), the highly valuable methyl bromide is linked to the depletion of atmospheric ozone, and, under the U.N. Montreal Protocol it is scheduled for banning in 2005.[16]

Because of the side effects of chemical use and the high costs of dealing with the risks, California agriculture has developed a wide array of nonchemical methods to address pest problems. One approach is biological control. This area, while holding much promise, needs increased research emphasis, particularly in understanding the role of plant systems in a total ecological system.

Integrated Pest Management. Integrated Pest Management (IPM) has been an important development in pest management philosophy that integrates several tools to address pest problems. Researchers in the University of California have been

[16] California strawberry growers and others have sought a special use exemption, such that they might be permitted to use methyl bromide beyond 1995, but it is not expected to be available for application in the long run. California growers have applied about 16 million pounds of methyl bromide per year, about one half of the national total. Strawberry growers account for about one-third of California's use. Carter (2001) suggests that a methyl bromide ban would result in a 15 percent reduction in the value of strawberry production.

experimenting with and promoting these techniques since the 1950s, and since the early 1970s IPM practices have become viable. Currently, IPM is practiced in one form or another by more than 50 percent of the state's growers. The University of California has a large IPM program, to promote and expand IPM use.[17]

The key components of IPM are the monitoring of pest populations and treatments of pest problems according to natural conditions. The technology combines a wide variety of tools: biological control, agricultural practices, the use of pheromones, and, when needed, the use of chemical pesticides.

The introduction of IPM has led to several institutional innovations in California agriculture. First, two new professions have emerged: agricultural scouts who monitor pest populations, and pest control consultants who recommend pesticide use. Large growers may employ their own in-house scouts and consultants, but scouts and consultants are also employed by dealers, and there are also independent consultants. Recently, the State imposed certification requirements on pesticide consultants.

Biotechnology. Agriculturists in California and worldwide are recognizing that reliance on chemical pesticides will decline over time, and greater attention is being given to research on alternative technologies. Biotechnology has provided some widely used alternatives to chemical pesticides in California and is likely to provide many more options in the future. For example, the bacteria *Bacillus thuringiensis* has been introduced to combat pests in several crops, including cotton, corn, and tomatoes.

California growers have been among the first to adopt certain new genetically engineered pest-resistant or herbicide-resistant crop varieties, and California has played some leading roles in biotechnology research. The first genetic manipulation of crops to gain much attention was the research in strawberries conducted by the University of California. The first agricultural genetic engineering company formed was Calgene. However, as in the medical biotechnology area, the most successful agricultural biotechnology companies established in California were later purchased by large multinationals.

Computers

Much of the computer revolution in the past 30 years originated in California; the Silicon Valley itself previously contained flourishing fruit farms. Nevertheless, California farmers have adopted computer technology only gradually in their enterprises, and the potential for computerization in many California agricultural industries has not been fully realized.

In general, farmers initially use computers for bookkeeping and accounting functions, with production management activities coming later. Currently, only a small percentage of farmers use computers intensively for production management.

One exception is the dairy industry, where the use of computerized herd improvement programs is widespread. Dairy farmers had intensive manual bookkeeping systems and herd improvement activities before the introduction of the

[17] In a recent study of the returns to pest-management R&D conducted by the University of California, Mullen et al. (2003) documented the pivotal role of UC leadership in the development and adoption of IPM not only in California but more generally in the United States. The study emphasizes IPM as an element of the University's total effort in pest-management R&D, and documents case studies for several commodities.

computer; thus computerization simplified existing operations. (In other management applications, computerization may significantly alter production processes and decision making.) Another reason for the popularity of computerized herd improvement programs is that the software, to a large extent, was provided by the public sector and promoted heavily by the Extension Service. That is not the case with other production management applications.

Private-sector innovations are often embodied in capital goods, public-sector innovations less so. Computer software falls in between. Programs can be easily copied, and they are not very well protected by patent laws. Public universities have not put much effort into developing computer software for farm management; to a large extent, the perception is that such activity should be left to the private sector. (Indeed, in the UC system there is not much emphasis on the general area of farm management either in research or extension.) Most agricultural software companies, in most cases, develop production management software in response to clients' specific needs. Several past attempts to develop more general production management software were unsuccessful, perhaps because of limited computer literacy among farmers.

The largest farms have been the leaders in the use of computers for both business and production management activities; some employ programmers and/or software experts. Smaller operations frequently rely on consultants, and a significant number of small agricultural software and consulting businesses have sprung up throughout the state. The future of computer use in California agriculture appears quite promising, especially since serious experimentation with precision agriculture is taking place.

Livestock Production Technology

To a great extent livestock production technology is not as location-specific as cropping technology. California's livestock industries have evolved in much the same ways as throughout the United States. Technological change has been especially important in the most intensive livestock industries—broilers and hogs, in particular. In the dairy industry, California has developed and improved its technology more rapidly than the rest of the United States. Milk production has grown relatively rapidly, dairy is now the largest agricultural industry in California, and California is now the largest and lowest-cost dairying state in the nation. Technology in dairy feed production, milk harvesting and milk handling, has improved in a number of ways. California leads the nation in large-scale, intensive dairy production. Family-owned dairy operations may milk up to several thousand cows, in some cases three times a day, with computerized recording of the production by each individual cow used to determine individual rations fed (in the bale) during milking. The typical midwestern dairy farm, by contrast, still operates with fewer than 100 cows in a grazing system.

SCIENCE POLICY

The technologies that have played such an integral role in the development of California agriculture have been developed through synergism between public-sector institutions and private-sector investments. Government has played a role by creating appropriate incentives for private firms to conduct their own research and development (R&D) and develop products and technologies for which they can be rewarded by the market, as well as by financing and conducting public research in areas where the private sector cannot or will not invest. Science policy encompasses public-sector R&D plus decision making relating to private R&D, intellectual property rights, and technological regulation. Because agriculture and agricultural markets are evolving along with society, social attitudes, and science itself, science policy must evolve as well.

Research Institutions

In the United States, both State and Federal governments are extensively involved in agricultural R&D. The main form of involvement is the government production of agricultural science—in government labs or in public Universities—using general government revenues. This is justified both in principle and by the evidence that the rates of return to public agricultural research have been very high—even with very extensive government intervention to correct the private-sector under-investment in agricultural R&D. This evidence suggests that the government intervention to date has been inadequate, that it could have profitably spent much more on agricultural R&D.

It is not sufficient to argue that the government should spend more on agricultural science. Important issues include: What research should be done? How should public agricultural R&D be managed to make sure that the net benefits are maximized from the limited funds that are available? Who should provide those funds and how? In terms of government policy, these issues can be couched in terms of questions about:

1. the institutional arrangements that are put in place to determine the total funds made available for public agricultural R&D, the allocation of those funds among research institutions and across research projects and programs, among fields of science, and between research and extension;
2. how the public resources are managed and used (and whether this will be done efficiently and effectively to obtain the greatest possible net benefits);
3. property rights regimes that will strengthen private incentives for invention.

An important element of this institutional structure is the division of labor between Federal and State governments, in terms of both the funding and the execution of public agricultural R&D. If results from research are widely applicable in the nation, it may be best financed federally (perhaps done in USDA labs), but if it applies in only a small number of states, the Federal role might be limited to encouraging States to cooperate or do more than they would otherwise (e.g., by providing funds for State research).

Many crops grown in California are special to it; thus California has developed its own unique institutional arrangements for research. The California Agricultural Experiment Station (CAES), spread over the campuses of UC Berkeley, UC Davis, and UC Riverside, is the state's main institution for public agricultural R&D. CAES research and Cooperative Extension are supported through a combination of Federal, State, and private funding, but the State provides the lion's share. The University of

California is the largest public university in the world, and the CAES is the largest public agricultural research enterprise based on the U.S. land grant system model.[18]

Global and National Context

Pardey and Beintema (2001) discuss trends in R&D policy and spending more broadly, and provide important data on global trends in agricultural R&D and private-versus public-sector spending patterns, as well as longer-term trends in U.S. public agricultural R&D. A brief review of these elements from Pardey and Beintema provides a context and perspective for contemplating California's agricultural R&D policy patterns.

In 1995, about $490 billion dollars was spent on all the sciences worldwide, which is about 1.6 percent of global GDP in that year (or $1.64 per 100 dollars of GDP). Rich countries did the preponderance (i.e., about 85 percent) of this research (the U.S. share alone was 42 percent), and rich countries only devote a small share (3 percent) of their total research expenditure to agricultural R&D compared with less-developed countries (17 percent).

Growth in spending on all science stagnated during the 1990s. Agricultural science shared in this stagnation, but in some countries was hit harder than more general science (medical and military research are the big ticket items). This has been associated with general economic conditions and a waning public enthusiasm for science generally, but also a decline in political support for publicly funded agricultural R&D in many countries, and within that, a shift away from public funding of "near-market" research. In the United States these trends have been less pronounced than in some other countries, but recent years have seen a tightening of support, from both Federal and State governments for funding agricultural research and extension. Agricultural R&D has lost ground recently relative to other non-defense research, especially the National Science Foundation and the National Institutes of Health.

Global spending on agricultural R&D in 1995 was about $33 billion, about one-third ($11 billion) private and the remaining two thirds ($22 billion) in the public domain. The United States accounted for 19 percent of this global total in 1995, down from its 29 percent share two decades earlier. However, the United States commands an even bigger share of the private- and public-sector total—22 percent of the 1995 global total of $33 billion.

The private-sector share has been growing relatively rapidly, but this research takes place mainly in a small number of rich countries. In the United States, private agricultural research spending more than doubled in real terms from 1970 to $4.6 billion in 1998 (compared with $3.4 billion of public agricultural R&D in that year). This growth has been associated with improvements in intellectual property rights (especially pertaining to plant varieties), and modern biotechnology, among other things. Table 5 shows trends in U.S. public and private agricultural research funding. The public funding includes both State and Federal government funds.

Worldwide, public spending on agricultural R&D nearly doubled, in inflation adjusted terms from 1976 to 1995. It grew faster in less-developed countries, which

[18] A detailed history of the development of agricultural research in California is provided by Scheuring (1995). A more general picture of the U.S. land grant system is provided by the Board on Agriculture (1996, 1997). Data on research investments are summarized by Mullen et al. (2003).

now account for more than half of public-sector spending (53 percent in 1995), though still less than half of total agricultural R&D spending (37 percent in1995). Spending has stagnated since the mid-1990s and in some places has fallen in nominal as well as real terms.

Table 5. U.S. Agricultural Research Funding in the Public and Private Sectors, 1970-1998: Millions of real (1998) dollars

Year	Public R&D Funding	Private R&D Funding	Total R&D Funding
1970	2,450	2,120	4,570
1975	2,820	2,427	5,247
1980	3,217	3,419	6,636
1985	3,341	3,756	7,097
1990	3,540	4,048	7,588
1995	3,750	4,598	8,348
1998	3,648	4,887	8,535

Source: National Research Council (2003, pp. 190-191).

Importantly, in recent years, the U.S. public sector has been declining in relative and perhaps absolute importance as a source of new agricultural technologies. The rising importance of private-sector investments in proprietary technologies will have important implications for the balance in the types of technologies that are being produced and to whom they are available. In particular, subsistence crops in developing countries and specialty crops in places like California are more likely to become technological orphans in the changing institutional structure.

National Trends in U.S. Public Agricultural Research and Extension

U.S. Federal intramural research is conducted by the Agricultural Research Service (ARS), and the Federal Government also helps fund agricultural research at State Agricultural Experiment Stations (SAESs) through four major mechanisms:

1. *Formula funds* allocated to States by formula;
2. *Competitive grant funds* allocated by panels of relevant scientific peers after consideration of research proposals submitted to the review panel;
3. *Special grants* provided to SAESs, other public institutions, and individuals to study problems of concern to USDA, as specifically designated by Congress;
4. *Cooperative agreements* between USDA agencies that perform research and SAESs.

While farm acts authorize certain levels of USDA funds to be used for particular programs, actual expenditures are set annually by agricultural appropriations acts.

In 1889, shortly after the Hatch Act was passed, federal and state spending appropriations totaled $1.12 million. Over a century later, in 2000 the public agricultural R&D enterprise had grown to over $3.5 billion, an annual rate of growth of 7.81 percent in nominal terms and 4.29 percent in real terms. In recent years total spending on public agricultural R&D (including extension) stalled, in real terms growing by only 0.12 percent per year during the 1990s. The slowdown began at least a decade earlier. Intramural USDA and SAES research accounted for roughly the same share of public research spending until the late 1930s, after which the SAESs' share grew to 72 percent of total public spending on agricultural R&D by 2000. The general trends include: a long-term trend for the SAESs to grow relative to the USDA intramural research; a decline in USDA intramural research since about 1980; a slowdown in growth in the SAESs since 1980, and a stagnation in the 1990s.

The USDA also contributes substantially to financing the SAESs. Of the funds spent in the SAESs in 2000, 30 percent was from federal sources, 47 percent from state government, and 22 percent from industry, income earned from sales, and various other sources. The share of SAES funds coming from federal sources has been declining recently, and the composition of those funds has changed too, with an increase in competitive grants and a decline in formula funds.

The federal government is also involved in financing extension conducted by the states. In 1915, the first year in which federal funds were made available for cooperative extension between the USDA and various State extension agencies, almost $1.5 million dollars of federal funds were combined with $2.1 million dollars made available from various state and local government sources for a total of $3.6 million. This total grew by 3.76 percent per annum to reach $1.6 billion by 1999. The public provision of extension services in the United States is essentially a state or local activity. Consequently, funds from within-state sources accounted for 74 percent of the total funds for extension with federal funds accounting for the remaining 26 percent in 1999.

Table 6. Research, Education, and Economics by Agency for FY 1985-2001 Budget Authority, millions of real (year 2000) dollars

Year	ARS	CSREES	ERS	NASS	Total
1985	915	1,123	81	101	2,220
1990	846	1,029	69	91	2,035
1995	914	1,102	64	96	2,176
2000	903	1,091	64	100	2,158
2001	970	1,095	65	96	2,226
2002	1,157	958	65	106	2,286

Source: National Research Council (2003. pp. 186-187).

Table 6 shows the components of the USDA's Research, Education, and Economics budget, expressed in real 2000 dollars including allocations for intramural research by the Agricultural Research Service (ARS) and the Economic Research

Service (ERS) and for the collection of statistics by the National Agricultural Statistics Service (NASS) as well as allocations to the Cooperative State Research Education and Extension Service (CSREES), which administers formula and competitive grant funds for research and extension conducted by states.

California's Agricultural Research Investment Patterns

Trends in California's public research and extension expenditures are summarized in Table 7, in both real and nominal terms.

Table 7. Public Research and Extension Expenditure in California, 1970-1997

Year	Nominal Research Expenditure	Nominal Extension Expenditure	Real Research Expenditure	Real Extension Expenditure	Real Total R&E Expenditure
	(current dollars, millions)		*(year 2000 dollars, millions)*		
1970	30.7	14.0	113.1	51.5	168.6
1975	48.5	20.6	129.4	55.1	184.5
1980	77.6	34.3	145.5	64.5	210.0
1985	118.6	50.1	172.0	72.7	244.7
1990	171.6	63.7	212.1	78.8	290.9
1995	191.0	63.2	208.2	68.9	277.1
1997	205.5	69.0	215.5	72.4	287.9

Source: Mullen et al. (2003, pp. 23-24).

From 1970 to 1997, in real (year 2000) dollar terms, California's public agricultural research expenditure almost doubled, from $113.1 million to $215.5 million (i.e., by a factor of 1.9). Over the same period, California's public agricultural extension expenditure increased much more slowly, from $51.5 million to $72.4 million (i.e., by a factor of 1.4). The total expenditure on research and extension increased from $168.6 million to $287.9 million (i.e., by a factor of 1.7). However, most of this growth, especially in extension, took place in the 1970s and early 1980s. Real extension expenditures in 1997 were roughly equal to their 1985 values, and real research expenditures in 1997 were very close to their 1990 values. The longer-term trends reflect a shift in emphasis toward research relative to extension, and a shift toward a shrinking share of funds from the federal government as a share of total funding for public agricultural research and extension in California.

The 2002 Farm Bill provides for a continuation of the recent past and the trends that have been evident over the past 20 years. Specifically,

1. Stagnant total real federal support for agricultural research and extension

2. A declining share of extension in the total
3. A declining share of formula funding in the total (no change in the formulas)
4. An increasing share of competitive grants in the total
5. Increasing application of constraints on the use of competitive funds
6. Increasing Congressional earmarking of funds

These factors combined mean little total growth in funds available from the federal government for agricultural R&D, and an ambiguous effect on the efficiency with which those funds are being used. The state budget crisis in California has exacerbated the funding situation. Together these factors have resulted in a significant reduction of funding for research, and especially extension, in California, with cuts over two years (FY2002-03 and FY2003-04) in the range of 20 percent for research and 35 percent for extension. Further cuts may be anticipated in future years.

California's public research and extension is mainly undertaken through the UC Division of Agriculture and Natural Resources (ANR). In FY2001-02, ANR reported the spending of $336.4 million, of which $240.6 million was spent on CAES research, and $92.0 million was spent on cooperative extension.

The sources of funds for CAES research have varied over time. The biggest single source of funds is provided through the state legislature, accounting for about two-thirds of the total funds going to CAES in recent years. The areas of most rapid growth in non-federal funds are from the sale of products (such as royalties from plant variety patents) and from industry grants and agreements, including check-off funds (marketing orders for a number of California specialty crops raise funds for both research and promotion). Industry-sourced funds now account for over 10 percent of the total CAES research budget.[19]

In recent years, some large distributors of high-value crops have developed their own research and are trying to establish their own fruit and vegetable varieties. Some of these producers have even signed technology transfer agreements with the University, hoping to establish proprietary rights. There is a growing effort in the University to encourage commodity groups and cooperatives to invest in R&D. [20]

Public- and Private-Sector Partnerships and Technology Transfer

The rise of genetic engineering has encouraged closer collaboration between public and private enterprises in research and product development, at least partly because of the profit motive. Technology transfer activities, which are already significant in medical biotechnology, are starting to take place in the agricultural sector. For example, university researchers who discover the specific properties of a gene or develop a new product apply for a patent. The UC Office of Technology Transfer then can sell the rights to use the products, and to take advantage of the patents, to private companies. The University of California has engaged in several such arrangements,

[19] Commodity marketing order funds collected as check-offs on each unit sold have been used much more extensively for commodity promotion than for research (see Lee, Alston, Carman and Sutton, 1996), but in several industries are a primary resource for applied commodity-specific research. Check-off funding is much more highly developed and heavily used for financing agricultural R&D in Australia (Alston and Pardey, 1996).

[20] For more details on technology transfer and the evolution of biotechnology, see Postlewait, Parker, and Zilberman (1993) and also Parker, Zilberman, and Castillo (1997).

and the University receives significant royalties, for example, from rights to use its strawberry varieties.

Much more radical and exciting biotechnologies are now being developed, as for instance new pest-control alternatives. Some organizations that are considering biotechnology transfer agreements with the University include chemical and seed companies. Some large food and vegetable marketers have bought rights to university-developed technologies, and some grower cooperatives are seriously considering investing in this area.

Private organizations are also tending to sponsor certain research projects in order to have the first right-of-refusal for the innovation that they produce. This practice has already occurred in the chemical and medical fields and seems to be occurring in agriculture. Furthermore, although most California grower groups in the past supported research at the University of California, they are undertaking research contracts with other universities. This may lead to more competition among universities, and may also alter the nature of university research from more basic toward more short-term, applied questions.

One of the most interesting trends in university research is growing transfer of rights to proprietary technology from the university to the private sector. University researchers, in many cases, develop patents that are basically concepts and ideas, and their commercialization requires significant investment. Companies will not engage in this investment unless they are sure that they will capture the benefits from the investment. Lack of investment in university technologies was one of the reasons that motivated the U.S. Senate to pass the Bayh Dol Act in 1980, and that gave universities the right for a patent of research financed with federal money.

Once this Act passed, the process of commercialization of university innovations accelerated. In many cases, universities do not sell the right to innovations to establish multinational companies, but instead university professors establish alliances with venture capitalists and start startup companies, which may become major players on their own (as in the case of Genentech, Sun Microsystems, and many others), or may be taken over by a multinational (as was the case with Calgene, that was taken over by Monsanto). Technology transfer has been a source of significant revenue to universities, and the University of California has been the leading income earner from royalties (in excess of $100 million annually—see Graff et al., 2003). Nevertheless, the royalties cover, at most, 2 percent of university expense on research, and the main benefit of technology transfer is that the university becomes a source of innovation and competitiveness. In many cases, the main threat to established companies is new innovations that originate at universities (Google that originated at Stanford, really reduced the market power of Yahoo!)

The technology transfer from the university to the private sector has been crucial for the evolution of medical biotechnology, and has been important in agricultural biotechnology. Many crucial ingredients of agricultural biotechnology (for example, the agricultural *biobacturium*), were patented by universities, but the rights were sold to private companies. Companies, such as Monsanto and Dupont, have invested in university technologies, and there has been a growing tendency for university-private-sector alliances. For example, several years ago Novartis gave the University of

California, Berkeley, $5 million annually for research for five years, where Novartis received the first rights to consider commercialization of the results of this research.

The success of technology transfer is a testimony to the complementarity between the university and private-sector research. Scientists are pursuing, as Graff et al. (2003) suggest, fame, fortune and freedom. At the university, they are rewarded, mostly, for original research and expanding the frontier of knowledge; working in private companies, scientists may have less freedom and fame, but more fortune, and their research is more restricted to enhance product development.

Public-Sector Intellectual Property Rights for Agriculture

It has been shown, for several lines of research, that the share of university patents is declining as the products mature. The infusion of funds, as well as access to intellectual property of companies associated with university private sector partnerships, have helped to enhance university research. But the increased privatization of knowledge has a significant size effect. There are barriers to access to technology, and sometimes university scientists may not be able to utilize technologies that were originated in the university but were transferred to the private sector. Furthermore, the increased reliance on private sector research for product development may result in "orphan crops," that may be too small to warrant private investment in product development, even though the total benefit to consumers and producers combined would justify the investment.

The specialty crops of California are examples of possible orphan crops, and indeed, the private sector has not invested much in biotechnology for such crops. In many cases, lack of access to intellectual property rights is an added barrier to investment in technologies for these crops by either the private or the public sectors. One solution that was introduced recently is the clearinghouse for Ag Biotech (see Atkinson et al., 2003), where universities have pooled their intellectual property together to develop a public sector "pool" of patents that will reduce reliance on private sector IPR, and increase the bargaining power of public sector research as they try to negotiate rights to private sector IPR. The organization PIPRA (Public Sector Intellectual Property Rights for Agriculture) also aims to develop precise technology transfer arrangements that would lead to universities transferring the rights to their innovations, only for applications that would be pursued by the private sector partners, and retaining rights for applications that are most likely to be pursued by others. Graff et al. (2003) show that universities have 24 percent of the patents in agricultural biotechnology, which is more than any private company, and thus, pooling their intellectual property rights together may be indeed a mechanism to enhance their productivity and independence in pursuing product development.

SUMMARY

California agriculture is a remarkable success story. Successful capitalization of the resources provided by the state's natural endowment depended on a combination of market opportunities, water availability, and production technology. Technology was also important in the development of critical transportation linkages and irrigation.

The transformation of California agriculture that began over one hundred years ago entailed the progressive adoption and adaptation of various types of new technologies, including mechanical innovations, new chemicals, biological breakthroughs, and information systems. Improved methods of production, in conjunction with changing markets for inputs and outputs, have promoted dramatic changes in the range, mix, and total value of California's agricultural products, with a concurrent reduction in the use of land and labor.

The value of agricultural production today is over twice what it would have been without post-war productivity improvements. These improvements have resulted from private and public investments in California and elsewhere, especially other countries sharing a Mediterranean climate, in a complex international web of agricultural research and technology development, where knowledge and ideas are constantly interchanged.

Of course, these changes have not been welcomed by all; there are always some who do not benefit from new technology. The agenda for agricultural R&D is shifting as a result of changing perceptions of science and society. While it remains important to continue to improve productivity, the new agenda stresses the importance of issues such as the environmental effects of agriculture, alternatives to agricultural chemicals, and food safety.

Simply sustaining productivity in the face of sharper demands for more environmentally friendly, safer production practices will provide challenges for the new century that will require technological solutions. Both the private and public sectors must sustain their commitment to, and their rates of investment in, the future.

The United States has in the past provided a substantial share of the world's agricultural research investments, and technologies produced in the United States have spilled over to many countries, especially in the developing world. The long-term trend is for a rising proportion of agricultural R&D to be conducted in the private sector, and this will have implications for the nature of research undertaken and the mixture of research products that are available and on what terms. Some countries (especially the world's poorest) and commodities (especially subsistence and specialty crops) are increasingly likely to become agricultural technological orphans in a world where research is conducted increasingly on a for-profit basis, and where technological regulation is progressively eliminating technological options and raising the cost of developing alternatives.

REFERENCES

Acquaye, A.K.A., J.M. Alston, and P.G. Pardey. "Post-War Productivity Patterns in U.S. Agriculture: Influences of Aggregation Procedures in a State-Level Analysis," *American Journal of Agricultural Economics,* Vol. 85, No. 1, February 2003.

Alston, J.M., P.G. Pardey and H.O. Carter. *Valuing California's Agricultural Research and Extension*. University of California Agricultural Issues Center Publication No. VR-1, Davis, March 1994.

Alston, J.M., G.W. Norton and P.G. Pardey. *Science Under Scarcity: Principles and Practice for Agricultural Research Evaluation and Priority Setting*. Cornell University Press, Ithaca, 1995.

Alston, J.M., H.F. Carman, J. Christian, J.H. Dorfman, J.-R. Murua and R.J. Sexton. *Optimal Reserve and Export Policies for the California Almond Industry: Theory, Econometrics and Simulations*. Giannini Foundation Monograph No. 42, University of California, Berkeley, February 1995.

Alston, J.M. and P.G. Pardey. *Making Science Pay: Economics of Agricultural R&D Policy*. American Enterprise Institute for Public Policy, Washington D.C., 1996.

Alston, J.M., J.A. Chalfant, J.E. Christian, E. Meng and N.E. Piggott. *The California Table Grape Commission's Promotion Program: An Evaluation.* Giannini Foundation Monograph No. 43, Giannini Foundation of Agricultural Economics, 1997.

Alston, J.M., C. Chan-Kang, M.C. Marra, P.G. Pardey, and T J Wyatt. *A Meta-Analysis of the Rates of Return to Agricultural R&D: Ex Pede Herculem*. IFPRI Research Report No. 113, Washington D.C.: International Food Policy Research Institute, 2000.

Alston, J.M. "Spillovers," *Australian Journal of Agricultural and Resource Economics* Vol. 46, No. 3. September 2002.

Antle, J.M. and T. McGuckin. "Technological Innovation, Agricultural Productivity, and Environmental Quality," *Agricultural and Environmental Resource Economics*, G.A. Carlson, D. Zilberman and J.A. Miranowski, (Eds.). Oxford University Press, New York, 1993.

Antle, J.M. and P.L. Pingali. "Pesticides, Productivity, and Farmer Health: A Philippines Case Study," *American Journal of Agricultural Economics* Vol. 76. August 1994.

Atkinson, R.C. and others. "Public Sector Collaboration for Agricultural IP Management," *Science* Vol. 301, 11 July 2003.

Barkley, A.P. "The Determinants of Migration of Labor Out of Agriculture in the United States, 1940-85," *American Journal of Agricultural Economics*, Vol. 72, August 1990.

Board on Agriculture. Committee on the Future of Land Grant Colleges of Agriculture, National Research Council. *Colleges of Agriculture at the Land Grant Universities: A Profile*. National Academy Press, Washington D.C., 1995.

----------. Committee on the Future of Land Grant Colleges of Agriculture, National Research Council. *Colleges of Agriculture at the Land Grant Universities: Public Service and Public Policy*. National Academy Press, Washington D.C., 1996.

Brennan, J.P. *Impact of Wheat Varieties from CIMMYT on Australian Wheat Production*. Agricultural Economics Bulletin No. 5, New South Wales Department of Agriculture, Sydney, September 1986.

Carter, C.A. "Costs Uncertain: Methyl Bromide Phase-Out Becomes Reality." *California Agriculture* Vol. 55, No. 3. 2001.

Carter, H.O. and G. Goldman. *The Measure of California Agriculture.* University of California Division of Agriculture and Natural Resources, Publication 21517, Oakland, revised edition March 1996.

Cochrane, W.W. *The Development of American Agriculture: A Historical Analysis*. Second edition. University of Minnesota Press, Minneapolis, 1993.

Constantine, J.H., J.M. Alston and V.H. Smith. "Economic Impacts of California's One Variety Cotton Law," *Journal of Political Economy*, Vol. 102, October 1994.

Craig, B.J. and P.G. Pardey. "Input, Output and Productivity Developments in U.S. Agriculture," Contributed paper to the conference on "Global Agricultural Science Policy for the 21st Century," Melbourne, Australia, August 1996.

Fuglie, K., N. Ballenger, K. Day, C. Klotz, M. Ollinger, J. Reilley, U. Vasavada, and J. Yee. *Agricultural Research and Development: Public and Private Investments under Alternative Markets and Institutions.* Agricultural Economic Report No. 735, Economic Research Service, United States Department of Agriculture, Washington D.C., USDA, 1996.

Graff, G.D., A. Heiman, and D. Zilberman. "University Research and Offices of technology Transfer." *California Management Review*, Vol. 15, No. 1, Fall 2002.

Graff, G.D., S.E. Cullen, K.J. Bradford, D. Zilberman, and A.B. Bennett. "The Public-Private Structure of Intellectual Property Ownership in Agricultural Biotechnology," *Nature Biotechnology*. 2003 (forthcoming).

Hayami, Y. and V.W. Ruttan. "Factor Prices and Technical Change in Agricultural Development: The United States and Japan, 1880-1960," *Journal of Political Economy*, Vol. 78, 1970.

Huffman, W.E. and R.E. Evenson. *Science for Agriculture: A Long-Term Perspective.* Iowa State University Press, Ames, 1993.

Hurd, B.H. "Yield Response and Production Risk: An Analysis of Integrated Pest Management in Cotton," *Journal of Agricultural and Resource Economics*, Vol. 19, No. 2, December 1994.

Johnson, S.S. *Mechanical Harvesting of Wine Grapes*. USDA-ERS Agricultural Economic Report No. 385, U.S. Department of Agriculture, Washington D.C., September 1977.

Lee, H., J.M. Alston, H.F. Carman and W. Sutton. *Mandated Marketing Programs for California Commodities.* Giannini Foundation Information Series No. 96-1. Giannini Foundation of Agricultural Economics, Berkeley, August 1996.

Martin, P.L. and A.L. Olmstead. "The Agricultural Mechanization Controversy," *Science*, Vol. 227, February 1985.

Mullen, J.D., J.M. Alston, D.A. Sumner, M.T. Kreith, and N.V. Kuminoff. *Returns to University of California Research and Extension: Overview and Case Studies Emphasizing IPM*. University of California, ANR Publication 3482, Oakland CA, 2003.

Musoke, M.S. and A.L. Olmstead. "The Rise of the Cotton Industry in California: A Comparative Perspective," *Journal of Economic History*, Vol. 42, No. 2, June 1982.

National Research Council. *Frontiers in Agricultural Research: Food, Health, Environment, and Communities.* Committee on Opportunities in Agriculture, Washington D.C., National Academies Press, 2003.

Olmstead, A.L. and P. Rhode. "Induced Innovation in American Agriculture: A Reconsideration," *Journal of Political Economy*, Vol. 101, 1993.

----------. "An Overview of California Agricultural Mechanization, 1870-1930," *Agricultural History,* Vol. 62, No. 3, 1988.

Pardey, P.G., J.M. Alston, J.E. Christian and S. Fan. *Hidden Harvest: U.S. Benefits from International Research Aid.* Food Policy Report. International Food Policy Research Institute, Washington, D.C., September 1996.

----------. "Summary of a Productive Partnership: The Benefits from U.S. Participation in the CGIAR." EPTD Discussion Paper No. 18, International Food Policy Research Institute, Washington, D.C., October 1996.

Pardey, P.G. and N.M., Beintema. *Slow Magic: Agricultural R&D a Century after Mendel.* IFPRI Food Policy Report, Washington D.C, 2001.

Parker, D.D. and D. Zilberman. "Biotechnology in a Regulated World," *Biotechnology Review*, Vol. 1, 1993a.

----------. "University Technology Transfers: Impacts on Local and U.S. Economies," *Contemporary Policy Issues*, Vol. 11, 1993b.

Parker, D.D., D. Zilberman, D. Cohen and D. Osgood. *The Economic Costs and Benefits Associated with the California Irrigation Management Information System (CIMIS): Final Report*. Department of Agricultural and Resource Economics, University of California, Berkeley, June 1996.

Parker, D.D., D. Zilberman and F. Castillo. "Offices of Technology Transfer, the Privatization of University Innovations, and Agriculture." Mimeo, Department of Agricultural and Resource Economics, University of California, Berkeley, 1997.

Postlewait, A., D.D. Parker and D. Zilberman. "The Advent of Biotechnology and Technology Transfer in Agriculture," *Technology Forecasting and Social Change*, Vol. 43, 1993.

Rhode, P.W. "Learning, Capital Accumulation, and the Transformation of California Agriculture," *The Journal of Economic History*, Vol. 55, No. 4, December 1995.

Scheuring, A.F., with C.O. McCorkle and J. Lyons. *Science & Service: A History of the Land Grant University and Agriculture in California*. University of California Division of Agriculture and Natural Resources, Oakland, 1995.

Schmitz, A. and D. Seckler. "Mechanized Agriculture and Social Welfare: The Case of the Tomato Harvester," *American Journal of Agricultural Economics*, Vol. 52, 1970.

Taylor, J.E. and D. Thilmany. "Worker Turnover, Farm Labor Contractors, and IRCA's Impact on the California Farm Labor Market," *American Journal of Agricultural Economics*, Vol. 75, May 1993.

Taylor, J.E. and D. Thilmany. "California Farmers Still Rely on New Immigrants for Field Labor," *California Agriculture*, September-October 1992.

Thilmany, D. "FLC Usage among California Growers under IRCA: An Empirical Analysis of Farm Labor Market Risk Management," *American Journal of Agricultural Economics*, Vol. 78, November 1996.

Thilmany, D. and S.C. Blank. "FLCs: An Analysis of Labor Market Transfers among California Agricultural Producers," *Agribusiness*, Vol. 12, 1996.

Thilmany, D. and P.L. Martin. "Farm Labor Contractors Play New Roles in Agriculture," *California Agriculture*, September-October 1995.

Zahara, M. and S.S. Johnson. "Status of Mechanization of Fruits, Nuts, and Vegetables," *Horticultural Science*, Vol. 14, No. 5, October 1979.

Zilberman, D., J.B. Siebert and A. Schmitz. "Economic Perspectives on Pesticide Use in California: Overview and Conclusions," Chapter 1 in *Economic Perspectives on Pesticide Use in California*. Giannini Foundation Working Paper No. 564, University of California, Berkeley, October 1990.