troduction of pollen-bearing plant parts into archeological sites by the sites' inhabitants can distort the pollen ratios. Second, the concept of changes in seasonal precipitation patterns was developed on the basis of pollen analyses in the Sonoran Desert (69). However, the Cheno-Am and Composite species of the desert differ compositionally and phenologically from their counterparts on the Colorado Plateaus (R. H. Hevly and L. E. Renner, *Mus. North. Ariz. Res. Rep. 18*, in press). Third, reconstructions of dendroclimatic variability for the Mesa Verde [H. C. Fritts, D. G. Smith, M. A. Stokes, *Mem. Soc. Am. Archaeol. 19* (1965), pp. 101-121], Santa Fe (49), and northwestern New Mexico (M. R. Rose, in preparation) areas lend little support to the idea of systematic shifts in seasonal precipitation patterns. Fourth, J. E. McDonald [*Univ. Ariz. Inst. Atmos. Phys. Tech. Rep. 1* (1956)] has shown that Southwestern winter and summer precipitation are independent of one another. Thus there is no reason to expect winter precipitation to decrease when summer rainfall increases or vice versa.
85. The most obvious discrepancy between the Black Mesa area and Navajo Reservoir records occurs in the period before A.D. 500 where some ^{14}C dates from Navajo Reservoir archeological wood samples uncorrected for terminal ring dates differ by more than 100 years from associated archeologically dated materials. Schoenwetter's generalized climatic curve (Fig. 4, column 5D) shows wetter than present climate during the late Los Pinos phase (A.D. 300 to 400) and the *w/x* interval. However, some archeologically dated pollen assemblages indicate arid to semiarid conditions during late Los Pinos and early Sambrito phase times (43). This appears to be consistent with hydrological evidence for lower San Juan River water levels during the late Los Pinos phase (43, 53) and with the *w/x* drought (Fig. 4, column 5C). Other discrepancies are apparent. Pollen spectra for the interval A.D. 950 to 1050 may erroneously indicate drier than actual conditions because of depositional contamination (79, p. 24). Two pollen spectra dated to the middle 1800's present conflicting evidence, one indicating moisture conditions similar to those at present, the other conditions wetter than those at present (79).
86. Hall divides the Chaco Canyon stratigraphy on the basis of local unconformities. Apparently no consideration is given to the equal stratigraphic importance of soil horizons that occur in broad-floored valley fills adjacent to active arroyos along the axial drainage lines. Hall's climatic inferences seem to be based in part on the assumption that arroyo cutting occurs in response to increasing moisture (83). Unfortunately, the Chaco Canyon pollen records of the last two millennia are not dated with the degree of resolution necessary to establish intercorrelations with the other pollen records discussed in this article.
87. Hall rejects this date (sample I-7301) and the date of 220 ± 110 B.C. from sample I-7303 on the basis of their apparent association with younger archeological materials. Sample I-7303 is from a horizon that contains dated archeological materials, and it clearly dates too early, probably because the sample represents old firewood. Sample I-7301 (A.D. 295 ± 85), however, should date earlier than A.D. 600 because it came from a level 22 to 32 centimeters below an archeological horizon dated at A.D. 600 or younger. Therefore, we accept the validity of this date.
88. R. H. Hevly and T. N. V. Karlstrom, in *Geology of Northern Arizona with Notes on Archaeology and Paleoclimate*, T. N. V. Karlstrom, G. A. Swann, R. L. Eastwood, Eds. (Geological Society of America, Flagstaff, Ariz., 1974), pp. 257-295. For a variety of reasons—including sampling interval differences, possible disturbance of sediments by currents and aquatic animals, and erosion of alluvial sections—the level of temporal resolution of detailed pollen records from regions adjacent to the Plateaus [J. R. Andrews, P. E. Carrara, F. B. King, R. Stuckenrath, *Quat. Res. (N.Y.)* **5**, 173 (1975); L. J. Maher, Jr., *ibid.* **2**, 531 (1972); K. L. Peterson, thesis, Washington State University, Pullman (1975)] is insufficient to reveal environmental fluctuations shorter than the ~ 550-year frequency. Therefore, these records are not directly comparable to the high-frequency Plateaus sequences considered here.
89. A. Serselj and D. P. Adam, *J. Res. U.S. Geol. Surv.* **3**, 737 (1975).
90. V. C. LaMarche, Jr., *Science* **183**, 1043 (1974).
91. Whether this apparent discrepancy represents real climatic differences or results from nonclimatic factors cannot now be determined because of the lack of comparable tree growth departure sequences from lower forest border trees elsewhere in California.
92. Similar population growth followed the construction of water-control systems during the period A.D. 1000 to 1050 in Hay Hollow Valley and in Chaco Canyon.
93. F. W. Eddy, *Southwest. Lore* **38**, 1 (1972).
94. ———, *Am. Antiq.* **39**, 75 (1974).
95. Correlations between secondary droughts and phase boundaries are particularly striking around A.D. 700 and 750 during the *X-2* interval; around A.D. 1000, 1050, and 1100 during the *Y-1* period; and around A.D. 1200, 1250, and 1300 during the *Y-2* interval. Data from Canyon de Chelly (16) suggest similar relationships around A.D. 1600 during the *Z-1* period and around A.D. 1800, 1850, 1900, and 1950 during the *Z-2* and post-*Z* intervals.
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98. J. T. Hack, *Pap. Peabody Mus. Archaeol. Ethnol. Harv. Univ.* **35** (No. 1), 85 (1942).
99. A. H. Rohn, *Cultural Continuity and Change on Chapin Mesa* (Regents Press of Kansas, Lawrence, 1977).
100. B. Bannister, *Southwest. Monuments Assoc. Tech. Ser. 6* (1965), part 2.
101. D. A. Breternitz, F. W. Eddy, W. J. Judge, W. D. Lipe, and A. H. Rohn reviewed all or parts of the archeological summaries. R. Hereford, H. E. Holt, B. C. Philpott, P. J. Schafer, C. G. Ami, and D. A. June—members of the Black Mesa Surficial Geology Project funded by the Energy Lands Program of the U.S. Geological Survey and directed by T.N.V.K.—contributed observations and samples used in the reconstruction of hydrologic history. H. E. Malde, K. L. Pierce, J. A. Schoenwetter, and D. S. Fullerton commented on the final manuscript. Most of the archeological fieldwork on Black Mesa was funded by the Peabody Coal Company of St. Louis. The dendroclimatic research was supported by grants to the Laboratory of Tree-Ring Research, University of Arizona; by the Advanced Research Projects Agency, National Science Foundation, and National Park Service. Support for some of the palynological studies at Northern Arizona University was provided by National Science Foundation grants to the Field Museum of Natural History and by McIntyre-Stennis funds made available to the Department of Biological Sciences by the School of Forestry. In addition, Northern Arizona University provided release time for the palynological studies. The Geological Survey provided support on a cost-share, mutual research interest basis for tree-ring research dating of alluvially buried trees by the Laboratory of Tree-Ring Research and for pollen analyses of Black Mesa samples by the Department of Biological Sciences at Northern Arizona University. We are grateful to these individuals and institutions for their many contributions to our research. This article has been authorized by the director, U.S. Geological Survey.

Economic Benefits from Research: An Example from Agriculture

Robert E. Evenson, Paul E. Waggoner, Vernon W. Ruttan

The nation is worried about productivity. The Council of Economic Advisors wrote in its 1979 report, "Between 1948 and 1965 [labor] productivity growth in the private nonfarm sector averaged 2.6 percent per year. In 1965-73 this rate declined to 2.0 percent. Since 1973, private nonfarm productivity growth has averaged less than 1 percent per year" (*1*). Research leading to technological innovation was identified as the primary source of earlier increases in productivity (*2*). The Administration has responded to the present decline by initiating an intensive review of federal policy affecting innovation (*3*). The three policies that have been suggested for accelerating innovation—government research grants, government laboratories, and tax credits (*4*)—imply a larger role for public research. Thus it is timely to analyze the long experience of public support for agricultural research.

Precisely because the public role is large in agricultural research, the data are available to analyze the economic returns from investment in research (Tables 1 to 3). Beginning in the 1950's with Zvi Griliches' estimation of economic return from research on hybrid corn, a substantial body of knowledge has been developed on rates of return on publicly supported research (Table 2). We now have enough information to test the consistency of the economic returns that have been calculated. Recent research (Table 3) has made it possible to go

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beyond simply estimating rates of return to investigating the effect upon those returns of such things as the mixture of science and technological research.

In this article we examine the changes in productivity in agriculture, the rate of return on agricultural research, and the manner in which the organization of agricultural research has influenced the rates of return. We relate the organization of the agricultural research system to its economic benefit. Finally, policy lessons are sought in the agricultural experience for a larger public role in other sectors.

Summary. In this article we examine the economic benefits of the long history of public research in agriculture. Agricultural productivity continues to grow. Annual rates of return on research expenditure are of the order of 50 percent. Research oriented to science is profitable when associated with technological research. Decentralization, as in the system of state agricultural experiment stations and substations, has allowed close association of research oriented to science with that oriented to technology and to farming. The high rate of return shows that investment in public research in agriculture is too low. This is at least partially because research benefits spill over to other regions and to consumers, reducing the incentives for local support.

Productivity Change in U.S. Agriculture

The changes in the productivity of American agriculture can be viewed in three ways (see Fig. 1 and Table 1). Crop production per acre of cultivated land is a common measure of agricultural production. Historically, land productivity grew little from 1870 to 1925. It then increased at 1 to 2 percent per year from 1925 to 1950. As Fig. 1 shows, productivity per acre increased rapidly during the 1950's and 1960's. In the early 1970's, as less-productive land was withdrawn from the soil bank, productivity per acre suffered. The increase in the 1970's has not been rapid.

The index of labor productivity—the ratio of output per unit of labor input—is a widely used index in both agriculture and industry. Figure 1 shows that the productivity of labor has grown more rapidly in agriculture than in industry since 1950.

A more inclusive measure of change in productivity is, however, required to measure the benefit of research. We shall use the index of total productivity, which is calculated by dividing the index of farm output by the index of total farm inputs. This index is published annually in *Agricultural Statistics* by the U.S. Department of Agriculture (USDA) and is examined at length in (*5*) and (*6*). The change in this index, which is shown in Table 1, is peculiarly suited to indicating the effect of research on efficiency because it measures change in efficiency, not change in farm income or prices.

From 1870 to 1900 farm output grew very rapidly but inputs grew rapidly also, producing a relatively slow growth of total productivity. From 1900 to 1925 inputs grew faster than output, and total productivity actually declined. During the 1930's, total productivity grew more than 2 percent per annum but failed to increase in the 1940's.

The change in total productivity in agriculture since 1950 is shown in Fig. 1. During the 1950's and early 1960's total productivity grew rapidly. During the late 1960's total productivity grew slowly, evoking a study of agricultural production efficiency (*5*). During the 1970's the total productivity index appears to have renewed its upward trend.

The continued increase in the productivity of labor in agriculture, and even more important, the increase in agriculture's total productivity, clearly merits investigation. In the following section we discuss how much of the change in productivity can be attributed to research.

Table 1. Percentage change per year in outputs, inputs, and productivities in U.S. agriculture (*21*).

Item	1870 to 1900	1900 to 1925	1925 to 1950	1950 to 1976
Land input*	3.1	0.8	0.1	−0.1
Land productivity	−0.2	0.0	1.4	1.9
Labor input†	1.6	0.5	−1.8	−4.1
Labor productivity	1.3	0.4	3.3	6.0
Farm output	2.9	0.9	1.5	1.8
Total inputs	1.9	1.1	0.3	−0.1
Total productivity	1.0	−0.2	1.2	1.6

*Cropland used for crops, including crop failure and cultivated summer fallow. †Number of workers, 1870 to 1910; man-hour basis, 1910 to 1976.

Contribution of Research to Increased Productivity

The contributions of research to increased agricultural productivity have been estimated by two methods. Table 2 provides a summary of 32 studies. Almost all investigators reported high returns on investment, well above the 10 to 15 percent realized on typical investments. The pattern of high returns extends across different commodities and countries, confirming both their generality and the strength of the methods used in their estimation.

The estimates classified as "index number" were computed directly from the cost of research on, say, hybrid corn, and the benefits were obtained from the estimated increase in production attributed to hybrid corn. Typically, the benefits and costs were assumed to continue indefinitely. The calculated returns of 20 to 90 percent are the average returns for every dollar invested. In these studies benefits are defined as the benefits for both producers and consumers.

The estimates classified as "regression analysis" were computed by a different method that permits estimation of the return from increased investment rather than the average return from all investment. Further, this method can assign parts of the return to different sources, such as scientific research and extension advice. Because regression methods are used, the significance of the estimated returns from research can be tested statistically. The dependent variable is the change in total productivity, and benefit is defined as the value of the change in productivity. The independent variables include research variables, which reflect the cost of research and the lag between investment and benefit. The objective of the regression procedure is to estimate that component of the change in productivity that can be attributed to research.

The estimates from regression analysis can be exemplified by the study of Japan, 1880 to 1938 (see Table 2). The money spent on research in Japan during this period was estimated to have increased the total productivity of Japanese agriculture and to have yielded a significant annual return of 35 percent.

The effects of the time and type of research, as well as the spillover effects, have been further analyzed in a recent study (*6*) more detailed than those referred to in Table 2. Changes in the productivity of American agriculture from 1868 to 1971 were related to the research performed by the state agricultural experiment stations and the USDA, agricultural extension, and the schooling of farmers. The results are shown in Table 3.

During the 1868 to 1926 period, the estimated annual benefits from $1000 spent on research in a typical year increased for 15 years, reached a maximum of $12,500, and then decreased to zero over 25 years. A 65 percent annual rate of return was realized on this investment. The timing of the benefits was estimated (by least square procedures) in the same way for all the lines of Table 3, but only the maximum benefits are shown.

From 1927 to 1950 the research was divided into two types. The first was called technology-oriented and was defined as research where new technology was the primary objective. This included plant breeding, agronomy, animal production, engineering, and farm management. The second type was called science-oriented. Its primary objective was answering scientific questions related to the production of new technology. Science-oriented research included research in phytopathology, soil science, botany, zoology, genetics, and plant and animal physiology in the state experiment stations or the USDA.

The science-oriented research analyzed here is conducted in institutions where it is closely associated with technology-oriented research. Thus it is possible that the results might not apply, or would apply with a longer time lag, to science-oriented research isolated by organizational or disciplinary boundaries.

From 1927 to 1950 technology-oriented research yielded a rate of return of 95 percent. During the same 23 years, science-oriented research yielded a 110 percent rate of return, even more than technological research. The period 1927 to 1950 was one of substantial biological invention, exemplified by hybrid corn and improvements in the nutrition of plants and animals and in veterinary medicine. It was also a period of rapid mechanization. It is important to notice that in Eqs. 1 to 4 in Table 3, science-oriented research does not have a significant independent effect. The high payoff to science-oriented research is achieved only when it is directed toward increasing the productivity of technology-oriented research.

Research conducted in one state changes productivity in other states. We call this "spillover." In Table 3 we give an estimate of spillover. For 1927 to 1950 we estimated that 55 percent of the change in productivity attributed to technology-oriented research from a typical state was realized within that state. The remaining 45 percent was realized in other states with similar soils and climate. The spillover from science-oriented research was considerably greater.

The 1104 observations of 1948 to 1971 for 48 states allowed still more detailed analysis. Technological research continued to yield returns of more than 90 percent. The payoff on research was especially high in the South, where research had lagged in earlier periods (*6*). Science-oriented research remained profitable as it interacted with technological research, but it was less profitable than during 1927 to 1950.

Evidence concerning the schooling of

Table 2. Estimates of the return from investment in agricultural research, obtained by using index numbers and regression analysis. Studies not referenced herein are summarized in (*22*, p. 5).

Investigator	Year	Country	Commodity	Period	Annual return (%)
		Index number			
Griliches	1958	United States	Hybrid corn	1940–1955	35–40
Griliches	1958	United States	Hybrid sorghum	1940–1957	20
Peterson	1967	United States	Poultry	1915–1960	21–25
Evenson	1969	South Africa	Sugarcane	1945–1962	40
Ardito and Barletta	1970	Mexico	Wheat	1943–1963	90
Ardito and Barletta	1970	Mexico	Maize	1943–1963	35
Ayer	1970	Brazil	Cotton	1924–1967	> 77
Schmitz and Schmitz	1970	United States	Tomato harvester	1958–1969	
			With no compensation to displaced workers		37–46
			Assuming compensation of displaced workers for 50 percent of earnings loss		16–28
Scobie and Posada	1978	Colombia	Rice	1957–1964	79–96
Hines	1972	Peru	Maize	1954–1967	35–55
Hayami and Akino*	1977	Japan	Rice	1915–1950	25–27
Hayami and Akino*	1977	Japan	Rice	1930–1961	73–75
Hertford *et al.**	1977	Colombia	Rice	1957–1972	60–82
		Colombia	Soybeans	1960–1971	79–96
		Colombia	Wheat	1953–1973	11–12
		Colombia	Cotton	1953–1972	None
Peterson and Fitzharris*	1977	United States	Aggregate	1937–1942	50
				1947–1952	51
				1957–1962	49
				1957–1972	34
Wennergren and Whitaker†	1977	Bolivia	Sheep	1966–1975	44
			Wheat	1966–1975	−48
		Regression analysis			
Tang	1963	Japan	Aggregate	1880–1938	35
Griliches	1964	United States	Aggregate	1949–1959	35–40
Latimer	1964	United States	Aggregate	1949–1959	N.S.‡
Peterson	1967	United States	Poultry	1915–1960	21
Evenson	1968	United States	Aggregate	1949–1959	47
Evenson	1969	South Africa	Sugarcane	1945–1958	40
Ardito and Barletta	1970	Mexico	Crops	1943–1963	45–93
Evenson and Jha	1973	India	Aggregate	1953–1971	40
Kahlon *et al.**	1977	India	Aggregate	1960–1961	63
Lu and Cline	1977	United States	Aggregate	1938–1948	30
				1949–1959	28
				1959–1969	26
				1969–1972	24
Bredahl and Peterson†	1976	United States	Cash grains	1969	36
			Poultry	1969	37
			Dairy	1969	43
			Livestock	1969	47
Nagy and Furtan†	1978	Canada	Rapeseed	1960–1975	95–110
Evenson and Flores†	1978	Asia-national	Rice	1950–1965	32–39
Flores, Evenson, and Hayami†	1976	Philippines	Rice	1966–1975	27
Flores, Evenson, and Hayami†	1976	Tropics	Rice	1966–1975	46–71
Evenson and Flores†	1978	Asia-national	Rice	1966–1975	73–78
Evenson and Flores†	1978	Asia-international	Rice	1966–1975	74–102

*See chapters in (*22*). †See (*23*). ‡Not significant, N.S.

farmers and extension advice is found in Eq. 3 in Table 3. The schooling of farm operators had a positive effect, as one would expect. The effect of extension education and farm management advice is complex: it was particularly beneficial in a state with both considerable technological research and farmers with little schooling, and the net effect of these interactions and the main effect of extension was beneficial.

The effect of decentralizing scientists and appointing them to substations was tested after the publication of (6) and is reported in Eq. 4 in Table 3. The question at issue is how a shift in the distribution of scientists between the central state station and substations would affect the productivity of technological research. In Eq. 4 the fraction in the substations is multiplied by technological research. The interaction was positive and significant, indicating that decentralization has had a positive effect on the productivity of state research systems.

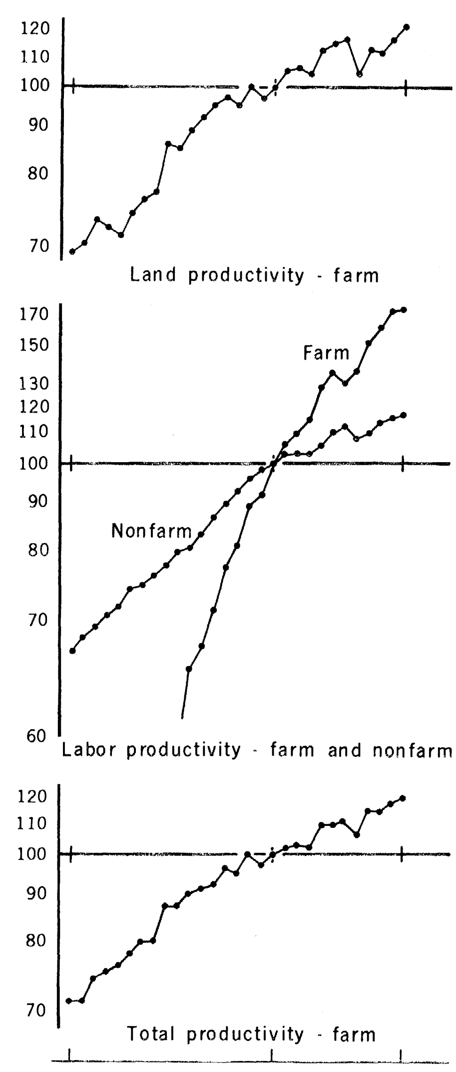
Character of Public Agricultural Research in the United States

Three characteristics are prominent in the American agricultural research establishment: It is articulated, decentralized, and undervalued. Descending from the Sanskrit word for arm through the Latin word for both division into joints and distinct utterance, "articulation" now means the state of being systematically interrelated into a whole as by joints and messages. "Decentralization" implies dispersion of authority and function at the regional or state level in contrast to centralization of authority and function; and "undervalued" describes an investment of low price and high earnings and indicates too little investment.

From their first settlements in America, the Europeans articulated science with farming. The first governor of Connecticut was a member of the Royal Society and reported his experiments with maize in the *Philosophical Transactions* in 1678. A Virginian reported the effect of soil on tobacco quality in the *Transactions* in 1688. During the first half of the 19th century, agricultural societies were formed, and they helped scientists report to Americans Liebig's theories of soil fertility. In 1835 a farmer became Commissioner of Patents and introduced scientific agriculture into the federal government via his office (7).

After seeing a Saxon *Landwirtschaftlich Versuchsstation* during his student years, a Yale professor led Connecticut to establish the first American experiment station. A dozen years later, Congress confirmed the existing articulation, and encouraged decentralization by enacting the Hatch Act for "experiment respecting the principles and applications of agricultural sciences," and thus causing stations to be established in every state (8).

The director of the first station wrote that an agricultural scientist "unites the requisites of the philosopher and the man



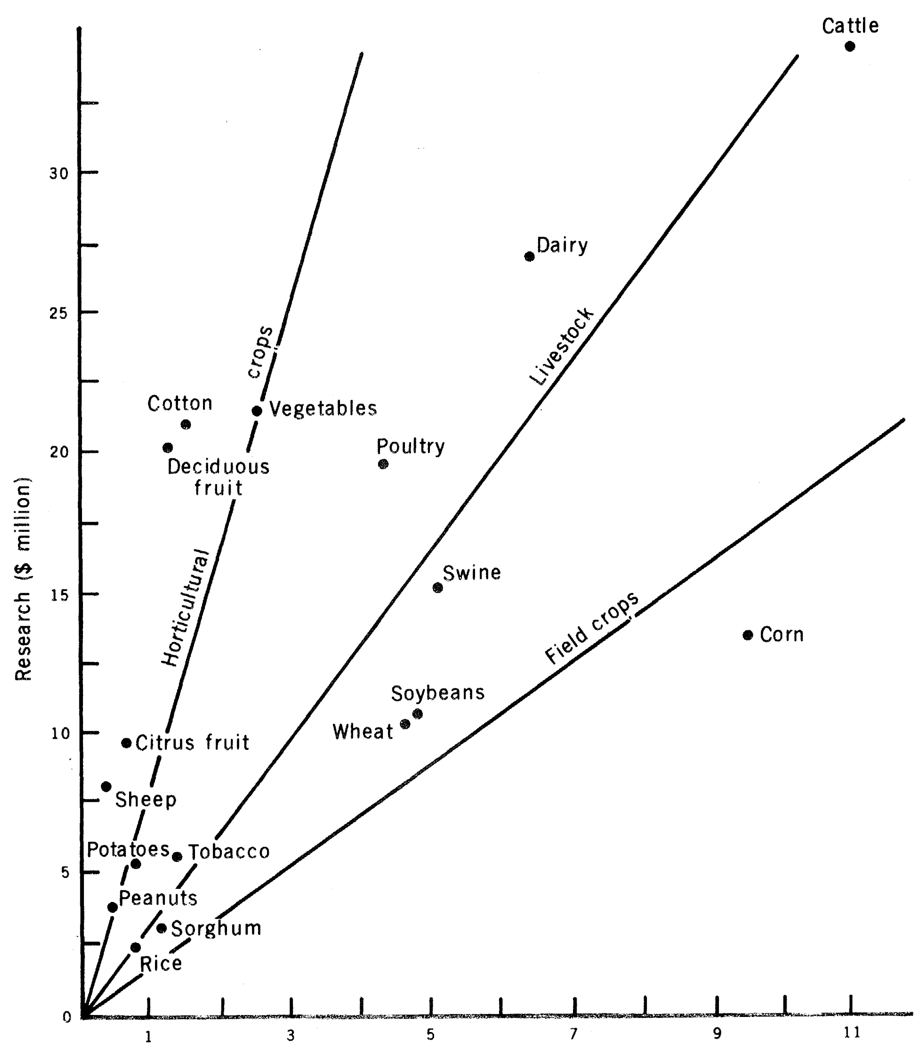


Fig. 1 (left). Productivity measures (1967 = 100). Fig. 2 (right). Expenditures (in 1967 dollars) of state stations and USDA on research on 16 products as a function of the gross income for the product in 1975 (24).

of business'' and possesses a practical knowledge of agriculture ''that he may be able to elucidate and elevate it by science'' (*9*). This articulation of theory with practice is exemplified by the scientist who invented double-cross hybrid corn, produced hybrid seed without detasseling, stated the principle of heterosis, belonged to the National Academy of Sciences, and answered garden questions in the *Rural New Yorker* (*10*).

In experiment stations the articulation can be seen in the names of such departments as ''Zoology and Entomology'' and ''Economics and Business''; or in such professional titles as ''Biochemistry and Bulb Physiology in Floriculture'' (*11*). The articulation can also be seen in the association between experiment stations and the extension services created by the Smith-Lever Act. In the agricultural research establishment there are connections and communications between theoretical research, practical research, and dirt farming.

The Hatch Act decentralized the establishment. It spread agricultural experiment stations across the nation. The efforts of the state stations are closely related to farming among states [illustrated by a correlation of $r = .79$ between farm income and station expenditures in 1975 (*12*)]. Further, many scientists of the USDA are dispersed, often in cooperation with the state systems. In contrast to this, space research in the United States was highly concentrated in one state; and in another nation, research in general was concentrated in government centers rather than located in centers of economic activity (*13*). A distribution of researchers exposes scientists to the problems of farmers, gives farmers and extension workers easy access to specialists and their libraries, spins off talent and ideas to a locality, and gives a region the technological capacity essential to development (*13, 14*).

Decentralization strengthened the articulation between science and farming. Although few experiment station directors have emulated the 19th-century director of the Wisconsin station who emphasized his affinity for farmers by wearing overalls when he sought money from the state legislature, most continue to pay careful attention to balancing effectively the mix in their research portfolios between science-oriented research and technology-oriented research that is expected to pay off in terms of state economic growth. Although the oversight exercised by legislative bodies has been weakened in much of the scientific enterprise (*15*), the articulation between legislatures, rural constituencies, and agricultural scientists has remained strong. Research by the USDA continues to respond to priorities expressed by the agricultural and appropriation committees.

State and regional interests are reflected in the use of the federal funds appropriated for use by the state stations. In 1975 two-thirds, or $85 million, of the federal funds available to the states was allocated by formula, rather than in the form of project grants, to the state experiment stations. There is probably even greater articulation between constituency interests and research supported in the case of the other funds of the state stations (Table 4). Two-thirds, or $282 million, of the total $413 million, was appropriated according to the evaluation of each station by state legislators. Private corporations and farm and trade associations provided $29 million, and fees for services and sales of products brought in $56 million. Finally, foundations contrib-

Table 3. Estimated impacts of research and extension investments in U.S. agriculture (*6*). The regression equations, standard errors of parameters (in parentheses), coefficients of determination (adjusted for degree of freedom), and numbers of observations (N) are as follows.

For 1868 to 1926,

$$P = 45.29 + \underset{(.162)}{.521}\, Inv + \underset{(.171)}{.813}\, Res + \underset{(23.38)}{3.04}\, Landq$$
$$R^2 = .634;\ N = 40 \text{ years} \qquad (1)$$

where P is the total productivity index; Inv is the index of inventions; Res is the stock of all agricultural research with time weights; $Landq$ is land quality; and R^2 is the coefficient of determination.

For 1927 to 1950,

$$\ln(P) = \underset{(.24)}{1.40} \ln(Inv) + \underset{(.037)}{.106} \ln(TRes) + \underset{(.0000033)}{.0000053} \ln(TRes)*(SRes)$$
$$R^2 = .503;\ N = 24 \text{ years} \times \text{four regions} \qquad (2)$$

where $TRes$ is the stock of technology-oriented research with time and pervasiveness weights; $SRes$ is the stock of science-oriented research; and * indicates that the variables are multiplied.

For 1948 to 1971,

$$\ln(P) = \underset{(.0085)}{.0331} \ln(TRes\text{-S}) + \underset{(.0085)}{.0119} \ln(TRes\text{-N}) + \underset{(.0089)}{.0187} \ln(TRes\text{-W}) + \underset{(.0710)}{.2061} \ln(TRes)*SRes$$
$$+ \underset{(.0426)}{.3540} \ln(Ed) - \underset{(.0097)}{.0394} \ln(Ext) - \underset{(.0021)}{.0116} \ln(Ext)*Ed + \underset{(.0230)}{.1821} \ln(TRes)*Ext$$
$$R^2 = .569;\ N = 23 \text{ years} \times 48 \text{ states} \qquad (3)$$

where S, N, and W are south, north, and west; Ed is schooling of farm operators; and Ext is extension and farm management research stocks.

The effect of decentralization is shown by

$$\ln(P) = \underset{(.0090)}{.0299} \ln(TRes\text{-S}) + \underset{(.0090)}{.0040} \ln(TRes\text{-N}) + \underset{(.0090)}{.0113} \ln(TRes\text{-W}) + \underset{(.0104)}{.5639} \ln(TRes)*SRes$$
$$+ \underset{(.0396)}{.5855} \ln(Ed) - \underset{(.0102)}{.02539} \ln(Ext) - \underset{(.0021)}{.0196} \ln(Ext)*Ed + \underset{(.0044)}{.1360} + \underset{(.00017)}{.00148} \ln(TRes)*Sub$$
$$R^2 = .595;\ N = 23 \text{ years} \times 48 \text{ states} \qquad (4)$$

where Sub represents substations.

Each equation also includes region and time period dummy variables. Equation 3 also includes a business cycle variable and a cross-sectional scaling variable [see (*6*) for details].

Subject	Maximum annual benefit from $1000 investment (dollars)	Annual rate of return (%)	Percentage of productivity change realized in the state undertaking the research
	1868 to 1926		
All agricultural research	12,500	65	Not estimated
	1927 to 1950		
Agricultural research			
Technology-oriented	11,400	95	55
Science-oriented	53,000	110	33
	1948 to 1971		
Agricultural research			
Technology-oriented			
South	21,000	130	67
North	11,600	93	43
West	12,200	95	67
Science-oriented	4,500	45	32
Farm management and agricultural extension	2,173	110	100

uted \$8 million. All in all, the stations have erected between themselves and the practical world few of the barriers described by Price (*15*).

The outcome of the articulation can be seen in the congruence between the value of a crop or animal and the money spent on research by the state stations plus the USDA (Fig. 2). As one would expect, more money is spent on research on livestock relative to their value than on field crops, and most is spent on horticultural crops, which are produced on small acreages, are subject to severe pest and disease problems, and have high requirements for quality. Within each of the three groups, however, there is congruence between research and value of the product.

The degree of congruence has grown closer in the 1965 to 1975 period even though research expenditures per dollar value of crops declined (Table 5). The changes in research expenditures were negatively correlated with the 1969 deviation from average research expenditure per value of commodity in each group ($r = -.69$). Tobacco was omitted from this calculation because it was subject to pressure from health policy. Research expenditures on tobacco fell relative to the value of the crop.

Final evidence of the articulation between the research establishment and practical interests can be seen in substations. Scientists have often argued that scientists at substations are too isolated from a scientific center to make significant scientific contributions. Farmers have countered that a single scientific center is too isolated from their farms to make important contributions to production. The balance of these considerations is shown by the state stations spending on substations \$41 million of the \$282 million appropriated by states in 1975 (*12*).

We have, therefore, a system of public agricultural research comprised of an industry leader (USDA), which conducts its research at widely dispersed locations, and 50 state-level "firms" whose product is viewed by its clientele as an input to state economic development. The articulation among the experiment station, farm and agribusiness clientele, and the state legislatures induces the director of, say, the Minnesota station to allocate resources to the end that Minnesota farmers will be competitive with Iowa corn producers and with Wisconsin dairy farmers (*16*). This articulation and response help explain the selection of the research portfolios that yield the high returns of Tables 2 and 3.

Evidence of economic benefit, however, must be the raison d'être for our writing, and we return to Table 3. The proposition that decentralization and articulation have increased economic benefit has been tested against the data for 1948 to 1971. The decentralization to substations had a significant positive effect, indicating that research is more productive as more is done in substations.

The benefit of articulation is also shown by the positive interaction between research and extension and between technology-oriented and science-oriented research (Table 3). The joining of research oriented to science with that oriented to technology did not emerge because scientists wanted it. Had the system not been influenced by its customers, it is evident from other experience that science-oriented research would have been institutionally separated from technology-oriented research. The supporters of technology-oriented research in the stations, however, had the wisdom to support related scientific research also and to insist that it be institutionally joined with technological research.

Table 4. Money available to state experiment stations and other eligible institutions in 1975 (*12*).

Source of funds	Amount (in millions of current dollars)
Specific federal grants	41
Federal formula	85
State appropriations	282
Private firms and associations	29
Fees and sales	56
Balances	39
Foundations	8
Total	413

Table 5. Expenditures on research by state stations and the USDA per thousand 1967 dollars of product (*24*).

Year	Field crops	Horticultural crops	Livestock
1969	2.66	12.57	3.01
1975	1.76	10.68	3.50

Table 6. The compound percentage increases of federal funds for research and development for three agencies (*25*).

Period	Agriculture	Commerce	National Science Foundation
1955 to 1975	5.4	10.4	18.4
1969 to 1975	1.6	13.0	6.1

We now come to undervaluation. Agricultural research is like an undervalued stock whose price-earnings ratio is low. In nearly every case in Tables 2 and 3 a nation could have expended its investment in agricultural research and earned a rate of return far higher than from almost any other investment. Yet Table 5 shows, for example, that the investment in research in the production of grain has decreased from \$2.66 to \$1.76 per thousand dollars of produce. Grain research is even more undervalued than before.

Price (*15*) has described how, after World War II, science was increasingly financed outside such mission agencies as Agriculture and Commerce. Money for research in Agriculture and Commerce increased more slowly than money for the National Science Foundation (NSF) (Table 6). From 1969 to 1975 the trend changed as the mission funds of the Department of Commerce grew faster than the nonmission funds of the NSF, but money for the mission of agricultural research scarcely increased despite rapid growth in agricultural exports and food crises of global dimensions in the mid-1960's and early 1970's.

Why, despite the high rates of return, does America continue to undervalue agricultural research and fail to increase its investment? One reason is spillover. Research paid for by one state increases productivity in other states, too. Although agricultural research, particularly of the applied sort, is relatively specific to a region, recent studies have demonstrated its spillover among states and even nations (*17*). Although the federal funds for state stations represent partial compensation for spillover, the present formula for distributing federal funds has still left agricultural research undervalued.

The division of the benefits from productivity growth between producers and consumers has also been important in weakening the support for agricultural research by farmers. If demand is elastic or growing rapidly, as when overseas markets are expanding, producers may retain a relatively large share of the gains from innovation. If demand is inelastic or growing slowly, as in the United States during most of the last 50 years, a large share of the gains will be passed on to the consumers in the form of lower commodity prices (*18*). Much of the political and legislative histories of farm support since the mid-1920's can be viewed as an effort by farmers to dampen or slow the transfer of the gains from productivity growth to consumers.

Since consumers have been the primary beneficiaries of agricultural research one would think they would insist on increased investment in research (*19*). The individual consumer, however, receives only his small share of the benefits from increased farm productivity. As a result, consumers have tended to support collective policy actions in support of agricultural research only when food prices rise rapidly. This support has been episodic. Thus, agricultural research remains undervalued by consumers as well as by producers.

Lessons from Agriculture

Although ancient and earthy agriculture would appear to be an improbable teacher of science policy, its continued productivity and its long experience with publicly supported research nevertheless recommend careful attention. Fortunately, its lessons can be taught in rates of economic return that have survived statistical tests of significance because the cost of the research has been posted to the accounts of science, commodities, and states and then published. The productivity data of the subsequent farming is also published, region by region and commodity by commodity. While the nation worries about declining innovation and productivity in all its economy, it is timely to seek the lessons of agriculture.

Three lessons can be discerned and they concern the articulation, decentralization, and undervaluation that characterize the American system of agricultural research. Articulation in the agricultural system is among scientists advancing knowledge, scientists inventing technology, and farmers producing food—all in the same locality. This is the articulation that yields economic returns (Table 3). Articulation in our analysis does not mean the firm control of the workers in every laboratory and plot by a programming office at the national research center. It also does not mean the close association of scientists in a scientific discipline whose research is subject only to review by peers (*20*).

Decentralization is essential for profitable articulation. Centralization of research for the industry of agriculture would stretch the present articulation between, say, Minnesota farmers and Minnesota laboratories so that it would lead to Washington and back and would ignore the evidence that even decentralization to substations is profitable. Centralization by scientific specialties would amputate the explorers of the unknown from the inventors of new technology, it would amputate the inventors from the farmers who must produce the returns, and it would ignore the evidence (see Table 3) that science-oriented research must be joined with technology-oriented research to produce benefits.

The history of agricultural research in the United States shows that the profitable articulation and decentralization are hard to maintain (*7, 8*). Farmers and their representatives must be induced to support investment in science whose benefits are both unknown and remote. Scientists must leave the security of laboratories to investigate dead calves and dusty fields with farmers. Federal officers must yield management to state officers. Nevertheless, the profitable articulation and decentralization have been created and maintained.

The third lesson is sobering. A beneficial system of public research continues to be undervalued. Despite annual returns of the order of 50 percent, which an economist would call clear evidence of underinvestment, investment remains static. We suggest two causes: (i) the benefits to farmers spill over across state lines to those who do not pay for the research, and (ii) the benefits to consumers are partitioned into such small amounts that the individual consumer cannot feel the connection. One could suggest that matching federal dollars to state dollars rather than vice versa as now would increase local influence and thus investment. But the present lesson remains: agriculture has not solved the problem of undervaluation of public research.

These are the lessons that a nation bent on increasing productivity by innovation can learn from agriculture. A public system of research can be decentralized in a manner that induces articulation among science, invention, and practice to yield great returns. But thus far, the system remains undervalued.

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