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Research and Productivity in Wheat and Maize

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A measure of agricultural research output in 75 wheat- and maize-growing countries was utilized to explain increases in yield per unit land in these crops over the period 1948–68. Several alternative specifications were tried, incorporating direct contribution of indigenous research as well as "borrowing" of outside knowledge. Statistical estimates are presented and their economic implications discussed.

Recent technological improvements in grain production were so dramatic as to give rise to the term "the green revolution" and to reward Norman E. Borlaug, undoubtedly the most important single contributor to this process, with the Nobel Peace Prize. The main feature of these improvements has been the breeding of new varieties for less developed countries and the transfer of genetic material across international borders. Starting with the Rockefeller Foundation program in Mexico and continuing with the International Rice Research Institute in the Philippines,[1] the development of the high-yielding varieties demonstrates the potential payoffs of the application of up-to-date biologic—mainly genetic—

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[1] See Ruttan (1971) for a short description of these institutions and additional references.

knowledge to hitherto neglected areas. Expectations about the continuation of this revolutionary process should, however, not be overoptimistic. A possibility that should not be discarded is that once the gap between the theoretical knowledge and the technical practice is bridged, advancements will come at a much slower pace and will, perhaps, depend less on breakthroughs resulting from concentrated international efforts and more on local selection, adaptation, and marginal improvements.

The experience of the green revolution intensified the efforts of agricultural technological change and focused the attention on the transfer of knowledge. This brought forth the crucial policy issues of optimal research effort and the mixture of indigenous research and borrowing of knowledge, issues that motivated parts of our analysis. But these are not new phenomena; indeed, scientific research has taken place in agriculture for a long time and improvements did occur, particularly after the Second World War, even if in a not-so-dramatic fashion. Our study covers the 21-year period of 1948–68, which the green revolution barely affected;[2] the average rate of growth of yields per unit area, over this period, was 2 percent per annum in the 64 wheat-growing countries and 3 percent for the 49 maize-growing countries of our sample, with several less developed countries exceeding these averages (see Appendix A).

This study is an attempt to estimate the contribution of "conventional" scientific research to agricultural productivity. Such estimates have been prepared for the United States (Griliches 1964; Peterson 1967; Evenson 1971), but, to our knowledge, no direct estimate has been prepared in an international context.

Background

The crucial problem in an empirical study is the availability and quality of data. We are engaged now in the collection of an international inventory of agricultural research data (Evenson and Kislev 1971): budgets, manpower stations distributions, etc. It is disappointing to discover how little has been done in documenting agricultural research work and how incomplete such an inventory will, by necessity, be. But even the best figures will suffer from comparability problems: the definition of a research worker and his typical training varies widely among countries, and expenditure data are plagued by exchange rate and accounting procedure problems. Moreover, these data cannot be divided by sector within the agricultural industry or by kind of work done.

[2] In 1968–69, the last year of the period, area sown to "green revolution" high-yielding varieties was less than 4 percent of the world's wheat-growing area (less than 4 percent in 1966–67). In India, however, this share reached 30 percent in 1968–69 (3 percent in 1966–67) (see Dalrymple [1972] for data on the spread of the new varieties).

An alternative measure of research work is the amount of work reported —the numbers of scientific publications. A few abstracting journals cover the fields of agricultural and biological research. Wheat- and maize-related publications were counted from *Plant Breeding Abstracts* (1932–69),[3] which attempts to cover all significant research work in plant breeding and related subjects in the world, and were classified by country according to the first author's address.

The use of "paper counts" as measures of research can, of course, be subject to criticism. In its defense we offer a few points. (1) The large numbers of papers published assure a substantial degree of regularity. (2) Most results of research work are published, though the publication system is, perhaps, biased in favor of the countries in which the professional journals are edited. (3) There is a "floor" to the quality of articles accepted by journals of international standing, and further screening by the abstracting journals helps to secure homogeneity. (4) Published papers represent research output, while manpower and expenditures are inputs. (5) This is the only way to get measures of crop-specific research.[4]

It should also perhaps be added that though articles in scientific journals are conveyors of information, some of them contain "intermediate knowledge" not directly applicable in production, and not all the contribution of research efforts to agricultural practices is contained in the published articles. But, in general, the work of a strong and well-trained scientific team of people who can identify and solve a crucial problem will result in scientific innovations worth reporting. If so, papers can serve as proxy measures of scientific work.

The restriction of the analysis to just two crops enabled the use of a simple physical measure of productivity—yield per unit land—and liberated the study from aggregation problems. This advantage was achieved at a cost: there are no crop-specific data on inputs other than land (area harvested). This shortcoming is not to be slighted; yet the importance of the omitted inputs should not be exaggerated either. An agricultural production process can be viewed as a mixture of two processes: a biological and a mechanical, with a production function of the form $Q = f[f_b(x_b), f_m(x_m)]$, where Q is output, b the subscript of the biological process, m the subscript of the technical, mechanical process, and x_b, x_m vectors of inputs. The inputs into the biological process (seeds, fertilizers, water, correct choice of methods, and timing) determine the potential yield; labor and machinery are inputs into the mechanical process that can be substituted for each other within the mechanical

[3] Counts of articles in *Field Crops Abstracts* (1948–69) were also tried in wheat (see Appendix A for summary data).

[4] Studies based on counts of articles are common in the area of the history of science; in fact, our attention was drawn to this approach by the studies of Derek J. DeSolla Price (1963).

process, but there is very little substitution between the two processes.[5] Our research measure is limited to biological work, and by omitting labor and capital we restrict the analysis to the biological subprocess.

The omission of fertilizers, water, and perhaps also an index of seed quality, pesticides, and similar biological inputs is, of course, more serious. However, to the extent that the adoption of these inputs is due to agricultural research (the development of fertilizer responsive varieties, for example), their omission is justified. We are interested in the total effect of research, including the indirect contribution through other inputs. However, these omissions will bias the estimates of research contribution upward.

An international comparison offers the opportunity to include "borrowing"—the transfer of knowledge—in the analysis. It is instructive to note at this point the differences in the transferability of the important aspects of knowledge in wheat and maize. Since wheat is self-pollinating, regularly harvested grains can be used as seeds and new varieties "diffuse" easily from farmer to farmer. Hybrid maize seeds, on the other hand, have to be propagated by specialized agencies and distributed to the farmers. Moreover, wheat is much less locality specific than maize. Mexican wheat varieties are grown successfully from North Africa to India, while specific maize varieties have to be bred for the various regions of the same countries.[6]

Of course, not all knowledge is created in the experiment station and the scientific laboratory; much is done by commercial enterprises, and farmers also often contribute to knowledge and its refinement. The main thrust of this study is, therefore, twofold: (*a*) the test of the hypothesis that scientific work does affect productivity changes and (*b*) an attempt to estimate its contribution.

Formulation and Specifications

To analyze the relationships between agricultural research and yields, we start from a simple summary framework. Yields are functions of soil, climate, and technology. Soil and climate determine yield potential with a given technology. Weather causes year-to-year variations in yield.

[5] The hypothesis of the separation of the agricultural production function into two processes cannot be tested here (see Sadan 1970). This hypothesis is consistent with the recent analysis of Hayami and Ruttan (1971), whose major finding can be interpreted to mean that because of the corresponding factor-price relationships, American research was directed to advancements in the mechanical process; Japanese, to the biological one.

[6] Myren (1969) attributes much of the relative success and failure of the Rockefeller project in Mexico in wheat and maize, respectively, to these characteristics.

Shifting cultivation between different soils will also result in yield variations:[7]

$$y(t) = f[S(t), T(t)] + u(t), \tag{1}$$

where $y(t)$ = yield in year t, $S(t)$ = soil and climate (since the observations are on countries, this variable can be taken as "country-specific conditions"), $T(t)$ = technology, and $u(t)$ = random weather effect. Technology is the form in which knowledge is revealed in production and is a function of indigenously created and of borrowed stocks of knowledge:

$$T(t) = T[K(t), B(t)], \tag{2}$$

$$K(t) = \int_0^t p(s)\, ds, \tag{3}$$

$$B(t) = \int_0^t b(s)\, ds, \tag{4}$$

where $p(t)$ = flow of indigenously created knowledge and $b(t)$ = flow of borrowed knowledge.

Knowledge can be subject to depreciation and obsolescence which will require the inclusion of depreciation terms in (3) and (4). Also, if T is the "best" knowledge available—the "frontier of knowledge"—a lag operator may have to be included in (3) and (4).

Borrowing of knowledge depends on the existence, outside a country, of knowledge relevant to the country. The larger such a stock, the higher the marginal productivity of the borrowing efforts. Moreover, the rate of borrowing can be affected by own work—to do research one has to follow work done elsewhere.

To introduce the possibility of regional specificity of knowledge, crop areas in the countries were assigned to agroclimate regions. The regions were adopted from the work of Papadakis (1952). His classification covers five dimensions (see Appendix B) and permits alternative regional definitions by combining classificational dimensions. Two such alternatives, the two-dimensional 3 and 4 and the five-dimensional 1–5, are used in the analysis reported here in wheat and maize, respectively. A regional stock of knowledge is defined as

$$\tilde{R}_i(t) = \sum_j r_{ij} K_j(t), \tag{5}$$

[7] For notational convenience, in the general discussion t is treated as a continuous variable. It appears as a subscript in regression equations. Similarly, integrals in the general discussion are represented by sums in the regressions.

where r_{ij} is the share of country j's wheat or maize area which belongs to region i. The pool of specific knowledge from which a country borrows, by hypothesis, is

$$R_{ij}(t) = \tilde{R}_i(t) - r_{ij}K_j(t); \tag{6}$$

that is, it is the stock of regional knowledge less the country's own contribution.

To formulate the borrowing activity, a logistic "borrowing function" was specified:

$$B_{ij}(t) = \int_0^t \left[\frac{R_{ij}(s)}{1 + \alpha e^{-\beta p_j(s)}}\right] ds, \tag{7}$$

where $B_{ij}(t)$ is the borrowed stock and α, β are parameters. Note that borrowing is defined as a flow and is accumulated to a stock.

The borrowed stock of knowledge in a country is the weighted sum of the stocks borrowed from the different regions with the regional shares, r_{ij}, as weights:

$$B_j(t) = \sum_j r_{ij}B_{ij}(t). \tag{8}$$

The parameter $1/(1 + \alpha)$, the intercepts of the borrowing function, indicates the amount of borrowing a country can do in the absence of indigenous research. In the limit, as $p \rightarrow \infty$, the country borrows all of the regional pool. In the regressions, α and β were estimated by searching for the value that will yield the highest R^2.

Production conditions are quite diversified, even in the smaller countries, and the measure of knowledge should be corrected to take account of this diversity. Two deflators were used to this end, and the numbers of publications in a country were divided by these deflators. The first is the average crop (wheat or maize) area in the country over the period, $\bar{a}_j$ in country j (Appendix A, cols. 3, 8):

$$d_{1j} = \bar{a}_j. \tag{9}$$

The use of this deflator implies the assumption that crop production conditions vary with the area. This is not always a very good assumption; the United States and Soviet Russia lead the world in terms of the total number of papers, but with the use of this deflator they become relatively small producers of knowledge. Clearly, some countries have varied production conditions with small areas, while others have huge homogeneous areas.[8]

[8] In the absence of data on extension and other instruments of information dissemination or, alternatively, on the number of wheat or maize growers, the area deflators serve also as a proxy for ease (or, rather, the difficulty) with which knowledge is spread over the countryside.

TABLE 1
RATE REGRESSIONS (EQ. [11])

REGRESSIONS	WHEAT 1	WHEAT 2	MAIZE 3	MAIZE 4
R^2	.314	.341	.447	.507
Constant	0.020	0.020	0.012	0.011
Variables:				
Research	0.016	0.018	0.029	0.031
[K(68)]	(5.32)	(5.61)	(6.17)	(6.78)
Research × past yield increases	...	−0.435	...	1.264
[$\rho_0 \times K(68)$]		(1.57)		(2.36)

NOTE.—N observations: wheat 64, maize 49; deflator: area deflator (d_1). The estimates were prepared in two stages. In the first, the average rates of yield increases (allowing for area effects) were calculated for each country, for wheat and for maize from the equation: $y_j(t) = aA_j(t)e^{\rho t}u_j(t)$, where $y_j(t)$ = yield in country j in year t; $A_j(t)$ = area harvested; and $u_j(t)$ = disturbance. The estimated ρ_j values for the period 1948–68 are reported in Appendix A, cols. 2 and 7. In the second stage, eq. (11) of the text was estimated. Regression estimates of eq. (11) were weighted by the average square deviation from the regressions of the equation above for wheat and maize, respectively. Figures in parentheses are t-statistics.

Neglecting within-region diversification of production conditions, the number of regions in a country can also serve as a deflator. However, regions can vary a great deal in size, so the second deflator used was

$$d_{2j} = \frac{n_j}{\sum_i [(r_{ij} - \bar{r}_j)] + 1}, \tag{10}$$

where n_j is the number of regions in the country and $\bar{r}_j = 1/n_j$ is the average regional share. Thus,

$$\frac{1}{d_{2j}} = \frac{1}{n_j} + V_j, \tag{10'}$$

where V_j, like the variance, is a measure of dispersion. The inclusion of V_j corrects for unequal size distribution of regions.

Estimates

Regression specifications and estimates are presented and preliminarily discussed in this section; economic implications are brought forward in the next.

Two principal sets of estimates were calculated: (a) cross-sectional ("rate" regressions) reported in table 1; (b) combination of time series and cross sections ("yield" regressions) reported in tables 2 and 3.

TABLE 2
WHEAT YIELD REGRESSIONS
(EQ. [13], LOGISTIC BORROWING FUNCTION)

	LINEAR ($\alpha = 500$ $\beta = 6.0$)			DOUBLE LOG ($\alpha = 3{,}000$ $\beta = 2.0$)	
REGRESSION	1	2	3	4	5
R^2	.923	.923	.928	.8978	.8980
Constant	24.515	24.990	23.650	2.9494	3.0200
Variables:					
Area (A)*	1.2×10^{-4}	-1.8×10^{-4}	-1.3×10^{-4}	0.0386	0.0389
	(2.10)	(2.79)	(2.35)	(2.21)	(1.95)
Time (t)†	0.298	0.267	0.230	0.0159	0.0157
	(21.20)	(16.63)	(14.76)	(9.68)	(9.51)
Own research‡ [$K(t)$]	5.249	0.001	4.646	0.0359	0.0199
	(10.44)	(0.50)	(9.45)	(3.33)	(1.30)
Borrowed knowledge§ [$B_j(t)$]	...	7.2×10^{-4}	6.4×10^{-4}	...	0.0107
		(9.31)	(9.01)		(1.49)

NOTE.—N observations: 1,316 (64 countries, 21 years, 28 missing observations). Depended variable: average yield = 100/kg per hectare. Country dummies: 63 country dummy variables included in all regressions to represent variable s_j in eq. (13). Deflators: regression 1: area deflator; regression 2: $K(t)$, $p(t)$, regional deflator; regression 3: $K(t)$ area, $B(t)$, $p(t)$, regional deflator; regression 4, 5: none. Country dummies are included in all the regressions; α, β values were estimated in regressions 1 and 4. Figures in parentheses are t-values.

* Wheat area in thousands of hectares.

† Year t, t = 1, 2, ... 21.

‡ Sum of counts of *Plant Breeding Abstracts* from 1948 to year t.

§ As defined in eqq. (7) and (8).

TABLE 3
MAIZE YIELD REGRESSIONS
(EQ. [13], LOGISTIC BORROWING FUNCTION)

	Linear ($\alpha = 1{,}100$ $\beta = 2.0$)			Double Log ($\alpha = 4{,}500$ $\beta = 0.4$)	
Regression	1	2	3	4	5
R^2	.846	.848	.849	.8404	.8461
Constant	39.732	39.994	36.351	3.6322	3.5846
Variables:					
Area (A)	-4.8×10^{-4}	-5.2×10^{-4}	-1.1×10^{-3}	-0.0613	-0.0414
	(2.22)	(2.41)	(5.68)	(2.76)	(1.87)
Time (t)	0.360	0.337	0.337	0.0153	0.0149
	(14.82)	(13.76)	(13.61)	(6.80)	(6.77)
Own research	0.011	0.010	3.008	0.0507	0.0245
[$K(t)$]	(7.77)	(6.94)	(6.66)	(7.53)	(1.69)
Borrowed knowledge	...	1.5×10^{-3}	1.8×10^{-3}	...	0.0562
[$B(t)$]		(4.72)	(5.63)		(5.89)

NOTE.—N observations: 989 (49 countries, 21 years, 40 missing observations). For definitions of variables see table 2. Deflators: Regressions 1, 2: regional deflator; regression 3: $K(t)$ area, $B(t)$, $p(t)$, regional; regression 4, 5: none. Country dummies are included in all the regressions. Figures in parentheses are t-values. The α, β values were estimated in regressions 2 and 5.

The estimated weighted rate equation (table 1) was:[9]

$$\rho_j = a + bK_j(68) + c\rho_{0j}K(68) + u_j, \tag{11}$$

where $K_j(68)$ = stock of country j's knowledge in 1968: sum of counts of articles in *Plant Breeding Abstracts* from 1948 to 1968, ρ_j = average rate of yield increases over the period 1948–68, and ρ_{0j} = average rate of change of yield for the period 1920–39 (set at zero for countries for which earlier yields were not available).

The results in table 1 indicate positive relations between research and yield increases, both in wheat and in maize. With the introduction of ρ_{0j} (regressions 2, 4) the marginal contribution of the stock of knowledge becomes

$$\frac{\partial \rho_j}{\partial K_j} = b + c\rho_{0j}. \tag{12}$$

The negative c value in wheat indicates diminishing returns to research in countries that exploited their potential yield increases prior to the period studied. This is apparently not the case in maize. In this crop, past yield increases are positively correlated with marginal productivity of research in the later period. A possible explanation for this finding can be the complexity of the modern maize technology. Higher yield improvement in the past may be an indicator of the technological maturity of the country's agricultural industry—a prerequisite for successful absorption of sophisticated modern innovations.

As noted earlier, research's contribution can expect to be overestimated due to the omission of other yield-affecting factors. However, to the extent that "paper counts" measure research output with an error (random), the regression estimates are biased downward. The specification in table 1 may introduce another source of random errors, as there $K(68)$ stands for the stream of knowledge created which in turn affected yields over the 21-year period. This formulation implicitly assumes similar time patterns of research work in the different countries, which was not the case.

[9] Unweighted regressions and weighting by area were also tried. The table below gives R^2 values for regressions 1 and 3 of table 1.

		Weighted	
	Unweighted	By Area	By Average Square Deviation
Wheat.	.181	.007	.314
Maize	.351	.172	.447

Weighting did not improve the estimates of the yield regressions. We are indebted to Finis Welch for the suggestion to use the average square deviations as weights.

A more detailed analysis becomes feasible with the utilization of combinations of time-series and cross-sectional data. The regressions estimated were of the general form

$$y_{jt} = \gamma_0 + \gamma_1 A_{jt} + \gamma_2 t + \gamma_3 \frac{K_{jt}}{d} + \gamma_4 \frac{B_{jt}}{d} + \gamma_5 S_j + u_{jt}. \qquad (13)$$

The regressions were calculated in linear and in double-log (Cobb-Douglas) form. In the double-log form all variables, except time, were replaced by their natural logarithms, and one was added to all stocks K, B to avoid zeros.

Tables 2 and 3 report regression estimates for wheat and maize, respectively. A major contribution to the explanation of these regressions is due to the country-specific variable S_j. In the absence of this variable, R^2 is of the order of .4. This should be expected when countries differ substantially in their yield potentials (see cols. 1 and 6 in Appendix A). The inclusion of this variable converts the regression into a covariance analysis where the coefficients measure "within"-country effects. This eliminates biases that could have been introduced by correlation between knowledge (own or borrowed) and yield-level potential.

The area and time variables were always significant, though the first varies in sign. Research and borrowing are always positive and significant in most regressions.

All four estimates of the parameter α in tables 2 and 3 indicate intercepts $[1/(1 + \alpha)]$ of the borrowing function that are virtually zero. No borrowing takes place in the absence of indigenous research work. This somewhat surprising result was confirmed in all the empirical experiments conducted.[10]

The economic implication of the estimates reported in tables 1–3 will be discussed in the next section. Before turning to this discussion, a few words on hitherto unreported experiments are in order.

1. Several regional classifications were tried. It was found that the best results—in terms of R^2 and in terms of reasonable coefficients—were achieved in wheat with the two-dimensional 3 and 4 classification (Appendix B) and in maize with the five-dimensional 1–5 classification. These classifications were used in the analysis reported in tables 2 and 3 to construct the borrowing factor and the regional deflators.

The regional classification determines by how many other countries a unit of knowledge, a paper, produced in one country can be borrowed. Under the assumption that a paper has the same probability to be produced in any one of the countries in the sample (an alternative assumption can be that this probability is proportional to the current

[10] As the α values are not estimated at the sample means, they are subject to a larger error than indicated by the regression results.

distribution of papers), the expected number of borrowers of such a paper is 5.32 in wheat and 1.15 in maize. This expected value is termed here the "transferability factor" (Appendix C). These values of the transferability factors are slightly underestimated, since not all wheat- or maize-growing countries are included in our samples.

2. Counts of articles from *Field Crops Abstracts* were tried in wheat as alternative to counts from *Plant Breeding Abstracts* (averages of the two were also tried). Counts from *Plant Breeding Abstracts* proved a superior variable.

3. The element in the exponent of the borrowing function in equation (7) is the flow of knowledge created. An alternative formulation tried was to replace the flow by the stock $K_j(t)$, implying that it is not work done, but the amount of knowledge a country possesses that determines its borrowing ability. The flow formulation proved superior.

4. A "world stock of knowledge" defined similarly to the definition of the regional stocks was constructed and tried in the regressions. Two hypotheses were tried with this variable: (*a*) that countries borrow from a world pool over and above the regional borrowing and (*b*) that borrowing takes place from the world at large with no regard to regional pattern. These two hypotheses had to be rejected.

5. Several ways to introduce depreciation of knowledge or lags in its effect were tried, but with no improvements in the results. Similarly, experiments at constructing stocks of knowledge by accumulating flow prior to 1948 did not yield better results.[11] There can be two explanations to the outcome of these experiments. (*a*) The "noise" component in the data is too large to permit such fine distinctions. (*b*) Knowledge accumulated before 1948, mostly before the Second World War, was either obsolete or totally disseminated by 1948. Hence, all countries entered the period studied on the same footing, and this period is too short to reveal significant obsolescence phenomena.

Economic Implications

The economic contribution of knowledge varies considerably with the model presumed. To take direct contribution of own research in the linear model first, the marginal contribution of a paper calculated from (13) is

$$\frac{\partial y}{\partial p} = \frac{\gamma_3}{d} \frac{\partial K}{\partial p}, \tag{14}$$

[11] There is, however, a built-in lag in the data—the lag from the completion of a research work to its publication plus the lag from publication to the appearance of the abstract.

and, by construction, $\partial K/\partial p = 1$. Equation (14) is calculated in terms of yield per unit area. Total contribution in the country is

$$\frac{\partial y}{\partial p} A = \frac{\gamma_3}{d} A. \tag{15}$$

The area deflator $d = A$ (disregarding within-country variations in area) and γ_3, the regression coefficient, measures total contribution in the country. This is also true if the correct deflator is not equal, but only proportional, to the area, since the factor of proportionality will be incorporated in the estimate of γ_3. Hence, with the area deflator the marginal (= average, since this is in the linear model) productivity of research is the same for all countries.

The regional deflator is not proportional to the area (in many countries $d_{j2} = 1$), and if it is the correct deflator, the contribution of research varies with the crop's area, in many cases proportionally.

In the double-log model the regression coefficients are elasticities, measuring percentage increase in yield due to percentage changes in the stock of knowledge—whatever the deflator, and with country effect, with dummies included in the regressions, the constant-per-country deflator "washes out." The marginal contribution of a paper is exactly proportional to total production level of the crop.

In the rate-regressions model of table 1 (all area deflated), additional research will shift yield to new growth paths from the average rate of growth of 2 percent per year in wheat to 3.6 percent, and in maize from 3 to 5.9 percent. In absolute values, the marginal contribution of a paper depends, therefore, on the rate of change of yield and on the time elapsed from the year at which the knowledge was created. In table 4 the values of the marginal contribution are $1,581 and $2,330 in wheat and maize in the first year (the mean year of the sample, since these values are calculated for average yields) and $20,287 and $30,822 10 years later.[12]

The economic contribution of a scientific publication is composed, according to the model in the background of equation (13), of three parts: (*a*) direct contribution of indigenous research to productivity—indicated by the coefficient of $K(t)$ in tables 2 and 3; (*b*) the accelerating effect of own work on borrowing—the contribution of a unit in the exponent of the borrowing function; and (*c*) the contribution of research in one country to productivity in others—the marginal contribution of a unit of borrowed knowledge, $B(t)$, times the transferability factor which indicates how many such units a paper produced in one country can be

[12] These figures, the second pair, are biased upward to some extent; since, as the area unit is 1,000 hectares, they measure the average contribution of a paper when a group of one paper per 1,000 hectares is added to the stock of knowledge in a country.

TABLE 4

ESTIMATES OF MARGINAL CONTRIBUTION OF RESEARCH

		Wheat					Maize				
Regression Type	Deflator	Table	Regression	Direct Contribution* (1)	Accelerating Borrowing* (2)	Contribution to Others* (3)	Table	Regression	Direct Contribution* (4)	Accelerating Borrowing* (5)	Contribution to Others* (6)
Rate:											
(Year 1)	Area	1	1	1,581	...	...	1	3	2,330	...	...
(Year 10)	Area	1	1	20,287	...	...	1	3	30,822	...	...
Yield, linear	Regional area	2	2	14,308	152,073	19,122	3	2	74,094	12,590	7,777
		2	3	29,737	...	...	3	3	15,040	...	...
Yield double-log (geometric averages)	None	2	5	64,734	6,155	24,071	3	5	31,605	551	9,483
Yield, double-log (arithmetic averages)	None	2	5	19,341	44,554	2,390	3	5	7,575	57,830	1,038

NOTE.—See text for methods of calculation.
* Dollars per year per publication.

turned into times the borrowing factor $1/(1 + \alpha e^{-\beta p})$. Estimates of these three components are listed in table 4.

In the linear model, the indigenous stocks were deflated both by area and by the regional deflators; estimates for both cases are reported in the table. The unbiased estimate of $\bar{y}$ in the double-log model is its geometric mean. Accordingly, marginal contributions are usually calculated, for such models, at that point of the samples. However, the geometric mean will generally differ from the arithmetic, and this difference is a measure of the dispersion of the variable averaged (the arithmetic mean of the pair [5, 495] is 250, the geometric is 49.7). Yields per unit land vary much less than the stocks of knowledge which, by construction, start from small numbers for 1948 and grow to 1968. A better representation of the "typical country" is therefore given by the arithmetic averages. The estimates for the double-log model were therefore also calculated at these points of the sample.

Since the logistic borrowing function is nonlinear, the estimates in columns (2) and (5) were prepared by calculating the marginal contribution for each point of the sample and averaging (arithmetically or geometrically) these values. The average borrowing factor values used in columns (3) and (6) were calculated in the same way.[13]

The estimates in the last row of table 4 are probably the most "reasonable"; they are based on a double-log model that incorporates the assumption of diminishing marginal products. The total value of the contribution of a publication is $66,285 in wheat and $66,443 in maize, surprisingly close; the distribution of the economic contributions among their components is also very similar in the two crops. However, these estimates, unlike those of the linear model, do not incorporate any deflating procedure—they imply that the contribution of a unit of knowledge is proportional to the country's total output value of the crop regardless of the diversity of agricultural production conditions.

Elsewhere (Evenson and Kislev 1971) we have estimated average expenditures per publication to run from 30,000 to 350,000 U.S. dollars, with values for the high publishing countries around $100,000. In the absence of obsolescence, the figures in table 4 (for the yield regressions) are flow values of permanent income streams.[14] It is, needless to say, unrealistic to assume that knowledge is not subject to obsolescence and depreciation, but even if these streams last for only 20 years (the present sample period), the values in table 4 imply substantial returns to investment in agricultural research.

[13] The average values for the borrowing factor $1/(1 + \alpha e^{-\beta p})$ are linear model: wheat .442, maize .507; double-log model: wheat .229, maize .102.

[14] To the extent that obsolescence took place over the sample period, the estimated coefficients are adjusted for it, and if obsolescence will continue at the same rate, these estimates do represent permanent income streams.

This is evidently not the right framework in which to attempt a full-fledged calculus of "growth accounting," of the relative contributions of different factors to the growth rates in wheat and maize production. A rough indication of the magnitudes involved can, however, be obtained. In the double-log formulation of (13),

$$\frac{\dot{y}}{y} = \gamma_2 + \gamma_3 \frac{\dot{K}}{K} + R, \tag{16}$$

where R stands for the change in the other variables. The average value for $\dot{K}/K$ is approximately 10 percent, both in wheat and maize. Taking γ_2, γ_3 from the regressions without borrowing (table 2, regression 4; table 3, regression 4), one finds that the contribution of K to growth was in wheat 23 percent and in maize 33 percent of the "contribution" of the time variable.

This finding can be rephrased in the following way: The contribution of research and the factors associated with it was one-fourth of the contribution of factors associated with time in wheat and one-third in maize. That is, the increases in new and improved inputs—new varieties, fertilizers, knowledge—that were time related contributed to production four and three times more in wheat and in maize than the increases in these inputs that were statistically associated with the accumulated research work. This may seem like a modest contribution of research, but as the other findings show, research activity can still be very productive.

Concluding Remarks

We purposely did not follow the practice (which one suspects is not uncommon) of limiting the report to "reasonable" results. The crudeness of the data, the lack of information, and the absence of prior work in this area justified in our mind more than the usual dose of experimentation. The general conclusion that runs through all the findings supports the basic hypothesis tested: There is a strong and persistent relationship between agricultural research and biological productivity-yield in wheat and maize. This relationship exists both "between" countries and "within" countries over time.

The economic implications of the estimates indicate a substantial contribution of research to productivity. Even if the values in table 4 are exaggerated by a factor of two (due to the omission of fertilizers and other variables from the regressions), they will still indicate a high payoff to research work. A major component of research's contribution is through the acceleration of the transfer of knowledge. Little knowledge is borrowed if no indigenous research takes place. The possibilities for the transfer of knowledge are more restricted in maize than in wheat, as the lower transferability factor in this crop indicates.

The study raises several problems and points to areas in need of further work and clarification. Of course more and better data on agricultural research are essential to deeper understanding of this activity. Conceptually and empirically, perhaps the most immediate need is to get a better knowledge of the regional classifications and the appropriate deflators. Further clarification of this aspect of the "research on research," which should prove to be a fertile ground for collaboration of economists and biologists, is needed to gauge the effect and spread of knowledge between and within countries. This also brings up the question of the dissemination of knowledge and the interaction of research and extension. Data on extension are, however, harder to come by than data on research.

The restriction of the present study to wheat and maize enabled experimentation and a close examination that would not have been possible otherwise. But this restriction prevented the inclusion of other factors of production in the analysis. Work at higher levels of aggregation with more comprehensive data is now being conducted, and we hope to be able to report the findings in the near future.

Appendix A

YIELD, AREA, AND PUBLICATION IN WHEAT AND MAIZE BY COUNTRY

	Wheat					Maize			
Country	Average Yield (100 kg/Hectare) (1)	Rate of Change (2)	Average Area (1,000 Hectares) (3)	Field Crops (Articles) (4)	Plant Breeding (Articles) (5)	Average Yield (100 kg/Hectare) (6)	Rate of Change (7)	Average Area (1,000 Hectares) (8)	Plant Breeding (Articles) (9)
Albania	9.74	−.018	112	0	9	11.01	.007	147	19
Austria	23.79	.034	255	49	29	...	...	...	...
Belgium	35.77	.009	197	35	17	...	...	...	...
Bulgaria	16.69	.060	1,317	55	152	19.39	.073	681	291
Czechoslovakia	22.24	.023	770	54	89	25.24	.024	168	107
Denmark	40.15	.015	91	32	19	...	...	...	...
Finland	17.23	.012	188	31	58	...	...	...	...
France	24.86	.035	4,222	123	114	30.52	.063	661	167
Germany (East)	30.61	.019	449	22	18	...	...	...	...
Germany (Federal Republic)	31.65	.020	1,249	140	165	...	...	...	...
Greece	13.97	.026	1,056	2	10	12.59	.028	205	4
Hungary	16.66	.035	1,236	40	158	23.48	.026	1,245	269
Ireland	28.74	.028	128	15	14	...	...	...	...
Italy	18.38	.023	4,366	204	374	27.86	.058	1,174	497
Netherlands	41.12	.011	114	94	103	...	...	...	...
Norway	22.13	.035	14	18	26	...	...	...	...
Poland	16.89	.037	1,520	46	95	21.36	−.013	17	76
Portugal	8.18	.016	712	25	47	10.06	.024	479	20
Romania	12.92	.034	2,866	41	134	15.16	.055	3,313	330
Sweden	26.84	.037	308	105	145	...	...	...	...
Switzerland	31.11	.015	104	19	52	...	...	...	...
United Kingdom	33.87	.024	884	208	187	...	...	...	...
Yugoslavia	15.85	.039	1,919	53	107	...	...	...	...
Spain	10.08	.022	4,211	51	89	21.42	.039	408	53
USSR	10.20	.022	60,236	533	1,634	17.41	.049	5,857	1,934
Canada	13.73	.011	10,538	175	379	42.81	.031	206	139
United States	14.51	.027	22,482	518	945	33.18	.038	2,637	2,617
Argentina	12.97	.004	4,829	71	62	17.97	−.004	2,444	160
Brazil	7.27	.003	901	21	26	12.79	−.002	6,514	68
Chile	13.62	.016	803	11	32	22.59	.053	67	22
Colombia	8.83	.017	149	11	29	10.87	.015	806	70
Costa Rica	...	...	...	...	...	11.56	−.069	63	38
Ecuador	7.41	.054	64	0	3	...	...	...	...

El Salvador	...	...	...	...	...	10.27	.011	180	5
Guatemala	6.84	.031	34	1	4	8.34	.015	633	36
Honduras	5.78	−.006	2	0	0	7.76	.014	336	5
Mexico	15.82	.064	754	15	23	9.50	.040	5,884	193
Nicaragua	...	...	...	...	...	8.64	−.065	148	13
Panama	...	...	...	...	...	8.67	−.008	87	12
Paraguay	8.54	.030	8	0	0	...	...	...	...
Peru	9.59	.003	155	4	35	14.24	.003	269	52
Uruguay	9.16	.004	531	9	8	6.16	−.005	254	14
Venezuela	5.82	−.016	4	0	1	11.16	.031	367	19
Sudan	12.30	.041	25	0	0	8.83	−.031	23	5
UAR	22.72	.021	613	13	57	...	...	...	...
Cyprus	8.76	.019	72	0	4	...	...	...	...
Iran	8.36	.011	3,259	3	1	...	...	...	...
Iraq	5.38	.003	1,396	3	2	...	...	...	...
Israel	13.37	.068	55	17	25	25.82	.167	5	16
Jordan	6.19	−.005	234	3	0	...	...	...	...
Lebanon	8.42	.011	69	3	2	...	...	...	...
Syria	6.76	.005	1,261	1	0	...	...	...	...
Turkey	10.70	.005	6,964	5	6	13.41	.015	663	1
Burma	5.31	.000	50	0	0	...	...	...	...
China (Taiwan)	16.11	.051	15	1	21	18.81	.033	12	26
India	7.84	.019	11,078	240	331	8.72	.012	4,205	224
Indonesia	...	...	...	...	...	9.29	.003	2,522	14
Japan	21.81	.009	608	83	609	20.07	.050	40	101
Republic of Korea	14.25	.052	125	0	1	...	...	...	...
Pakistan	8.28	−.033	4,722	17	37	10.33	.002	469	56
Philippines	...	...	...	...	...	6.34	.037	1,652	52
Thailand	...	...	...	...	...	18.27	.019	247	4
Algeria	6.48	−.014	1,844	10	7	10.99	.023	6	11
Ghana	...	...	...	...	...	10.81	.018	190	8
Kenya	10.67	.005	110	15	39	19.20	.023	57	82
Mali	12.73	.024	2	0	0	...	...	...	...
Morocco	6.87	.007	1,565	12	10	6.03	.007	490	19
Senegal	...	...	...	...	...	8.13	.004	31	3
South Africa	7.10	.009	1,043	22	20	10.86	.027	3,746	161
South Rhodesia	22.34	.090	2	8	6	22.67	.061	15	120
U.R. Tanzania	...	...	...	...	...	11.83	.002	464	13
Tunisia	4.34	−.008	1,027	30	22	...	...	...	...
Uganda	...	...	...	...	...	11.02	.016	176	15
Australia	11.93	.001	5,674	232	223	20.05	.011	766	117
New Zealand	30.98	.015	62	25	56	45.60	.028	3	6

NOTE.—Average yield and area are for the period 1948–68 (*Field Crops Abstracts*, 1948–69; *Plant Breeding Abstracts*, 1932–69). Rate of change: ρ in eq. (11); and "articles" are sums of counts for the period 1948–68.

Appendix B

Regional Classifications[15]

1. *Winter hardiness*
   a) Too cold for winter wheat
   b) Sufficiently mild for winter wheat
   c) Sufficiently mild for winter oats
   d) Sufficiently mild for citrus
2. *Summer heat and duration*
   a) Too cool for wheat
   b) Sufficiently warm for wheat
   c) Sufficiently warm for maize
   d) Sufficiently warm for cotton
3. *Annual hydric index* (*annual rainfall/water need*)
   a) 0–0.09
   b) 0.10–0.22
   c) 0.22–0.44
   d) 0.44–0.66
   e) 0.68–0.88
   f) 0.88–1.32
   g) 1.32–2.64
   h) 2.64 or more.
4. *Seasonal distribution hydric index*
   a) Mediterranean (winter rains)
   b) Isohygrous (rain in winter and summer with humid spring)
   c) Monsoon (hydric index high in summer)
5. *Soils*
   a) Pedalfers
      i) Podsol
      ii) Braun Erde
      iii) Red
      iv) Laterite
      v) Black-Prairie
      vi) Reddish-Prairie
   b) Pedocals
      i) Chernozem
      ii) Chestnut
      iii) Brown
      iv) Reddish

Appendix C

The Transferability Factor

In the following equations, i = region index, j = country index, J = number of countries in the sample, I = number of regions, n_i = number of countries in region i, and r_{ij} = the share of country j in region i.

A typical event (with probability $1/J$) is that paper is produced in country k. Then r_{ik} of it is contributed to region i. The total transfer potential of this part of

[15] A five-dimensional classification is obtained by meshing all five classifications; a two-dimensional, by meshing any two classifications (source: Papadakis 1952).

the paper to the other countries in the region is

$$\left(\sum_{j}^{n_i} r_{ij} - r_{ik}\right) r_{ik}.$$

To get the expected value of the borrowing potential for the region i, calculate

$$\frac{1}{J}\sum_{k}^{n_i}\left(\sum_{j}^{n_i} r_{ij} - r_{ik}\right) r_{ik},$$

and the expected value for the sample is

$$\frac{1}{J}\sum_{i}^{I}\sum_{k}^{n_i}\left(\sum_{j}^{n_i} r_{ij} - r_{ik}\right) r_{ik} = \text{the transferability factor.}$$

Note that the term in parentheses is zero for regions with only one country.

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