Bulletin 758

SCIENCE
AND THE WORLD FOOD PROBLEM

ROBERT E. EVENSON

The Connecticut Agricultural Experiment Station, New Haven

This paper is based on the author's Lockwood Lecture delivered at The Connecticut Agricultural Experiment Station, April 18, 1974. It was also discussed at the Conference Values for an Age of Scarcity, Aspen Institute for Humanistic Studies, May 12-18, 1974.

SCIENCE AND THE WORLD FOOD PROBLEM

Robert E. Evenson

Starvation in sub-saharan Africa, Russian wheat purchases, Asian cereal grain production shortfalls, and high food prices throughout the world have heightened concern over the capability of many nations to produce adequate food for rapidly growing populations. The optimism created by the improved wheat and rice varieties which led to the "green revolution" just a few short years ago has vanished from much of the public discussion. Many do not expect the efforts of agricultural scientists to increase productivity sufficiently to maintain per capita food production in many developing countries.[1] But most scientists and scientific institutions would disagree with this popular viewpoint.

It is not difficult to conclude that the optimism created by the popularization of the green revolution was unwarranted. Virtually all knowledgeable observers would agree that the significant gains in production of wheat and rice in Asia during 1966 to 1971 do not guarantee further gains at the same high rate. Even amateur agriculturalists would not expect a small set of improved varieties to be superior to existing varieties over all soil and climate conditions in the region. Yet, many governments adopted policies of food self-sufficiency based in part on the supposition that these "miracle" grains would be diffused to all producing regions. We are now harvesting the consequences of this unwarranted optimism in the form of unwarranted pessimism.

The issue of concern in this paper, however, is whether a reasonably stable and systematic relationship exists between scientific research and a country's ability to convert its scare resources into food. The contributions toward an understanding of this issue, forthcoming either from the economic and scientific literature have been minimal. Economists have been all too content to focus attention on the consequences of efficiency improvements to the neglect of the process by which efficiency improvements are discovered.[2]

Scientists and historians of science have a good deal more to say on the issue, but this literature, too, is marked by a reluctance to "model" discovery. In fact, there is significant resistance to efforts to treat the work of scientists as economic activity. Much of this resistance is based on the typical perspective of the individual scientist who cannot accurately predict the nature and extent of scientific discovery. But this is not necessarily true for an aggregation of scientists; the discoveries of a number of scientists may have systematic and predictable outcomes.

Several studies of the contribution of agricultural research to improved production efficiency, i.e., lowering the real resource cost of producing food and fiber, have been based on the proposition that there is a statistical relationship between research activity and actual discovery (Evenson 1971, Griliches 1964, Peterson 1967 and Evenson & Kislev 1973). However, acceptance of these studies by the scientific community is conditioned by the judgment that the agricultural research in question is heavily "applied" and directed toward the discovery of particular techniques of production.

In the literature of science policy, science is differentiated from technology discovery on the basis of economic orientation. Scientific discoveries usually do not have direct economic applicability, while technological discoveries do. This distinction is misleading because it suggests that scientists are not motivated to discover knowledge of value to man, and that economic dimensions cannot be applied to their work. It is not true that discoveries which are in the form of abstract concepts or knowledge lack economic value.

A recent set of economic studies conducted by the author and a colleague (Evenson & Kislev, 1974) has attempted to develop and test a simple specification of the relationship between improvement in the production efficiency in agriculture and research directed toward that end. The specification incorporates internationally diffused technology and knowledge, as well as indigenously discovered technology and knowledge as determinants of economic performance. It was subjected to test with international data; specifically to data from developing countries. This paper summarizes this work and discusses the results in the context of the world food problem.

The Basic Specification

Changes in cereal grains production in a particular country are determined by changes in resources devoted to production such as labor, animal or mechanical power, fertilizer and water, and changes in techniques of production.[3]

Changes in techniques of production are either directly transferred from another country, or discovered through research located either in the country in question or in other countries with similar soil, climate and economic conditions.

Technology discovery can be regarded as a process of search subject to the existence of scientific knowledge. For a given stock of scientific knowledge of the researchers seeking new technology, the anticipated discoveries can be expected to have diminishing returns.[4] As the search for technology proceeds, the potential discoveries become "exhausted" and progressively diminish.

Changes in the stock of scientific knowledge will change the conditions or "structure" of technology discovery. The development of plant breeding programs based on inter-specific hybridization in several crops (e.g. hybrid corn) represents a clear case of a shift in the structure of technology discovery. Improvements in experimental design, improved scientific equipment, expanded stocks of genetic materials, more reliable estimates of heritability, and advances in the understanding of physiological characteristics of plants, for example, have obvious impacts on plant breeding and agronomy.

Such scientific knowledge has economic value, and in efficiently organized research systems, allocation of resources both to technology discovery and to the discovery of related scientific knowledge is guided to at least some extent by the relative values of the anticipated discoveries. This does not mean that it is easy to determine these values or that research system managers can achieve an "optimal" allocation of resources in terms of maximizing the value of discoveries; but given the state of uncertainty it appears that most agricultural research systems achieve a reasonable level of allocation efficiency.[5]

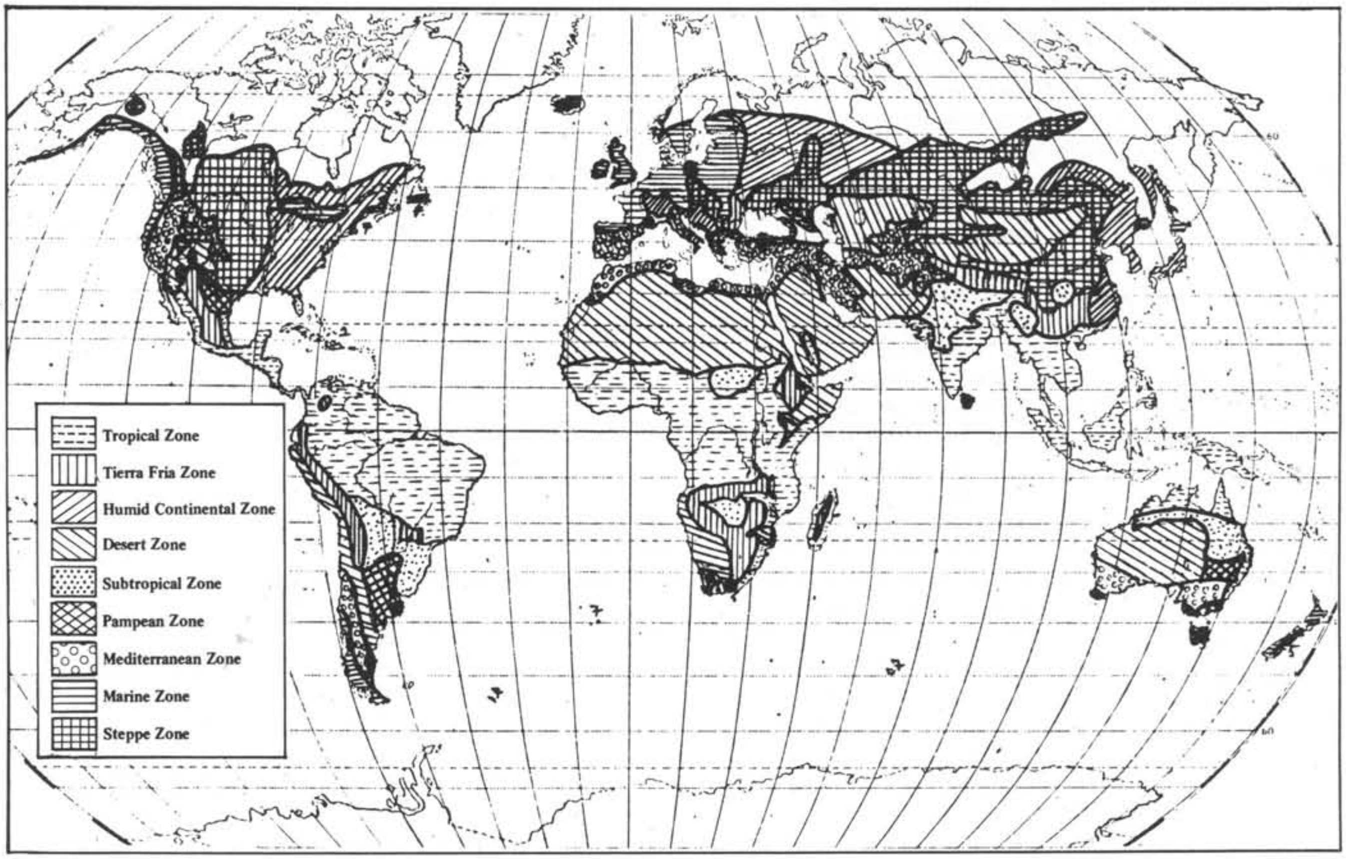
The Geo-Climate Factors

Before turning to a specification of the variables used in the study, it will be useful to discuss further the important principle of technology specificity. Simply stated, the efficient production of a unit of output depends on its price and the prices of the factors used to produce it. The techniques of production which maximize profit under one set of prices will not maximize profit under another. Furthermore, "new" techniques may be superior to existing techniques under one set of prices, and not under another.

This principle applies not only to prices, but to other conditions as well. Agricultural production technology is clearly specific to soil and climate conditions. Crop variety performance varies under different soil types, temperatures and water availability. Cultivation practices likewise are specific to geo-climate factors. Even on individual farms, several crop varieties and different types of seed bed preparation and insect control procedures might be used on a single crop because of variations in soil type and topography. Thus, newly discovered techniques will be superior to existing techniques only over a limited range of geo-climate and economic conditions. That is, even after the new techniques have been completely diffused, they will serve only a limited number of producers.

Many agricultural aid programs have been based on the expectation that extension agents, improved credit, and subsidies to modern input use, will facilitate the transfer of

Figure 1. Climate Zones of the World



technology from the developed to the developing countries. However, the evidence overwhelmingly supports the conclusion that these programs have facilitated little transfer and that the major barriers to transfer were not social or cultural. The bulk of the technology discovered in the developed countries has been too geo-climate specific to be transferable to the developing countries. The scientific knowledge upon which the discovery of the techniques is based, on the other hand, has much less geo-climate specificity.

A tremendous variety of information would be required to describe the specificity of actual techniques to these conditions. To simplify this study, cereal grains producing areas were classified into 33 major geo-climate regions and grouped in 9 geo-climate zones, based on the work of Papadakis (1966).[6] A summary of cereal grain production and related agricultural research is presented in Table 1.

This table shows the climatological description of the major climate zones and regions. For each region, measures of investment in research activities are reported as well as measures of crop production diversity within the region and measures of cereal grain yields at two different time periods. The term "sub-region" in the table refers to a crop-country-region observation. That is, a country producing all of its wheat in region 4.2 has one wheat sub-region. If the same country produces wheat in 4.3 as well, it has two wheat sub-regions. An adjustment (discussed in the footnotes to the table) is made for unequal sub-region size. Only those country-crop combinations of significant size are included in the table.

The table reports the share of the cereal grain acreage in each region which is produced in the developing countries. It is clear that climate and the level of development are related. Except for the sub-regions in the Mediterranean climate zone, production in a region tends to be almost exclusively in either developed or developing countries. The Tropical, Tierra Fria, Desert and Sub-Tropical zone sub-regions are primarily in developing countries while the Marine, Humid Continental and Steppe sub-regions are located in developed countries. The data showing the changes in average cereal grain yields per hectare indicate that yield levels tend to be highest in the major developed country regions; but more importantly that changes in yield from 1950-51 to 1966-67 have been greatest in the more developed climate zones.

The relationship between climate and the level of development has, of course, long been recognized. It is important, however, that we not draw the conclusion from this relationship that climate factors necessarily inhibit development. A further relationship is also evident in this table. It is that the willingness to invest in agricultural research is also related to climate factors. Most developing countries have simply not invested heavily in research to improve cereal grain productivity. This fact taken together with the limited transferability of technology across climate regions provides a basis for understanding the poor relative performance of many developing countries.

The measure of research reported in Table 1 is a tabulation of scientific publications from two major abstracting journals. Two types of research activity are indicated:

Agronomic and plant breeding research or A-type is measured by scientific publications on the five cereal grains classified by *Plant Breeding Abstracts* during 1942-70.

Related agricultural science research or S-type is measured by scientific publications on plant physiology, phytopathology and soil science abstracted in *Biological Abstracts* during the same period, but is not related to specific cereal grains. In defense of the use of publications as a measure of research activity:

1) The publications are "screened" by the abstracting journal. The editorial boards do not generally abstract low quality technical reports or material of purely local interest. The classification of plant breeding and agronomic publications (A-type) by crop orientation "selects" a particularly important kind of research clearly directed toward field crop technology.

2) That individual publications may vary greatly in scientific quality or economic importance is not important. As long as the distribution of quality is similar over time and across countries within the aggregate, the measure is valid.[7]

3) Scientific publications are the objective of a good deal of scientific work. The S-type researcher is motivated almost entirely toward publication. Granted that many A-type researchers are producing new crop varieties and other types of technology, it is still quite likely that the correlation between real new technology and A-type publications for national systems is quite high.

4) It simply is not possible to come up with a better measure of A-type research. Very few countries can produce data indicating the commodity orientation of the research supported, and for those that can, a serious problem of comparability exists. The measures reported here bypass these issues.

As Table 1 indicates, investment per sub-region for both A and S type research varies greatly. The major developed country regions in terms of production: (7.2, 7.6, 7.7, 8.1, 8.2, 9.2 and 9.3), range from 120 to 450 by this measure. By contrast, many of the major developing country regions have cumulated publications per sub-region below 30; many developing countries have virtually no indigenous research capability. In general, the ratio of S-type investment to A-type investment is considerably higher in the developed countries. Much of the S-type (perhaps one-third) research is conducted outside the conventional agricultural experiment station systems in these countries.[8]

The Empirical Results

Data by crop, by country, by year for most developed and developing countries, for the cereal grains wheat, maize, sorghum (millets), barley and rice, during the years 1948 to 1971 were subjected to regression analysis. The basic specification was

$$P = KL^{a_1}F^{a_2}A^{(a_3+a_4S)}RA^{(a_5+a_6ZS+a_7(A+S)+a_8(A+S)^2)}RY^{(a_9+a_{10}A)}$$

In this specification, P, K, L and F stand for the conventional determinants of production:

Table 1. Geo-climate Region Research In Cereal Grains Production

Climate Zone and Region	A-Type Publications (1942-70) per Sub-Region						S-type res. / A-type res.	Adj. No. of Sub-Regions	Developing Country Share	Cereal Grain Yields		
	Wheat	Barley	Maize	Sorghum	Rice	All Cereals				1950-51 (Kg/ha)	1966-67 (Kg/ha)	Ratio
1. Tropical Zone						48.3	.90			11.00	13.79	1.25
1.1 Humid Equatorial	––	––	30.2	11.6	111.8	51.6	1.06	15.91	1.00	11.92	14.33	1.20
1.2 Humid Tropical	1.5	.2	15.1	2.1	121.7	28.1	.32	5.00	.86	16.98	24.62	1.45
1.3 Dry Equatorial	––	––	4.7	1.1	22.5	8.2	1.53	4.06	1.00	10.61	14.53	1.37
1.4 Hot Equatorial	8.4	––	19.3	13.6	224.5	68.7	.96	10.22	.95	10.57	13.58	1.28
1.5 Semi-Arid Equatorial	.0	––	4.1	32.2	8.6	8.6	.65	6.35	1.00	8.46	10.69	1.26
1.7 Humid Tierra	20.4	20.4	30.6	26.0	20.8	24.1	.85	16.19	1.00	12.38	12.91	1.04
1.8 Dry Tierra	––	––	42.4	––	18.1	52.8	.50	2.06	1.00	14.49	10.11	.70
1.9 Cool Winter Tropical	––	––	18.5	87.4	353.1	144.9	1.00	5.58	.86	10.39	13.77	1.33
2. Tierra Fria Zone						52.1	.62			7.93	12.84	1.62
2.1 Tropical Highlands	8.0	6.7	132.9	28.2	––	52.1	.62	8.72	1.00	7.93	12.84	1.62
3. Desert Zone						15.6	2.69			9.22	12.05	1.307
3.1 Hot Tropical	.0	––	2.0	––	4.5	2.3	.22	3.00	1.00	28.28	31.86	1.13
3.2 Hot Subtropical	20.9	11.8	––	––	6.7	15.8	.76	16.94	1.00	8.99	11.80	1.31
	1.4	1.6	.0	.0	93.5	24.5	6.26	4.00	.60	9.98	11.83	1.19
4. Subtropical Zone						54.9	1.18			6.83	9.01	1.32
4.1 Humid	30.4	4.7	51.6	1.6	63.0	28.4	1.20	9.22	.75	12.50	15.65	1.25
4.2 Monsoon	116.6	128.1	69.7	144.9	52.0	102.7	1.31	6.91	.66	6.41	8.16	1.27
4.3 Hot	105.7	46.7	47.6	156.8	6.6	68.7	.99	6.05	1.00	5.21	7.41	1.42
4.4 Semi-Arid	––	––	10.0	5.0	––	7.5	.80	2.00	1.00	14.21	17.93	1.26
5. Pampean Zone						97.3	1.23			13.61	16.73	1.23
5.1 Pampean	99.5	99.0	168.4	36.6	––	97.3	1.23	4.53	.20	13.61	16.73	1.23
6. Mediterranean Zone						39.6	1.95			10.14	13.03	1.28
6.1 Subtropical	72.9	71.3	33.5	11.7	104.9	55.4	2.59	18.68	.45	10.38	13.10	1.26
6.2 Marine	14.0	2.2	34.4	12.0	.0	16.8	.80	7.24	.25	9.20	13.32	1.45
6.5 Temperate	77.3	18.9	45.5	4.0	23.5	37.4	1.90	11.27	.17	11.93	15.86	1.33
6.7 Continental	67.0	27.7	133.4	8.3	1.6	47.5	1.41	19.68	.30	10.79	14.48	1.34
6.8 Subtrop. Semi-Arid	46.9	22.8	21.3	6.0	––	26.7	1.68	14.26	.50	8.64	9.75	1.13
6.9 Contin. Semi-Arid	4.6	3.0	9.0	1.0	––	5.8	.20	4.61	.66	6.16	6.48	1.05
7. Marine Zone						120.1	2.02			17.01	28.13	1.65
7.1 Warm	11.5	5.4	––	––	––	8.4	2.00	2.00	.00	25.13	35.48	1.41
7.2 Cool	78.9	236.3	92.9	––	––	136.1	3.10	6.81	.00	22.12	34.82	1.57
7.6 Cool Temperate	97.1	145.8	158.9	20.3	––	120.3	1.75	21.71	.03	18.44	28.86	1.57
7.7 Cold Temperate	90.6	144.8	187.9	––	––	133.9	1.46	8.00	.00	9.62	20.79	2.16
8. Humid Continental Zone						256.2	2.79			19.61	34.02	1.74
8.1 Warm	152.4	151.2	450.5	92.2	417.0	254.3	4.60	7.62	.00	24.43	42.54	1.74
8.2 Semi-Warm	164.3	124.1	703.0	283.5	622.3	291.5	1.50	12.16	.00	18.77	33.55	1.79
8.3 Cold	52.0	17.0	––	––	––	34.5	.63	2.00	.00	7.98	11.90	1.49
9. Steppe Zone						357.9	1.35			11.57	18.26	1.58
9.2 Semi-Warm	606.5	346.6	818.6	304.2	24.7	450.3	1.10	12.92	.00	12.29	21.14	1.68
9.3 Cold	636.4	348.5	111.9	12.0	––	382.3	1.75	7.28	.00	10.11	14.82	1.47
9.4 Temperate	38.2	35.5	––	––	––	36.9	1.96	4.34	.00	11.85	17.36	1.47

Notes:
1. Publications data from Evenson, R.E. and Kislev, Y. (1971).
2. Sub-regions are defined as n(1-d) + d where n is the number of individual countries in the region, and

$$d = \sum_{i=1}^{n} A_i - \overline{A} / (2A_i - 2)\ \overline{A}.\quad A_i \text{ is the acreage of the crop in country i.}$$

3. The term d = 0, when all countries in the region have the same acreage, approaches 1 as acreage in the region is concentrated in one country.
4. Cereal grain yields are computed by simply totaling cereal production of the different grains without price weighting. While prices vary considerably by country, international prices per Kg are approximately the same for all cereals.

P is production of grain in time period t relative to the average production in 1949-50-51

L is acreage of each crop harvested in time period t relative to the average production in 1949-50-51

F is fertilizer consumption per acre of all grains in time period t relative to the average production in 1949-50-51

K is a constant term, which through the use of "dummy" variables, can take into account crop-specific factors.

Basically, the analysis is of changes in production over time. By expressing these variables relative to their 1949-51 average levels, factors which accounted for differences in these levels are cancelled out. The assumption is that climate, social and other factors which determined the 1949-51 differences in productivity did not affect the changes after that date (except through the research variables).

A is cumulated A-type research investment per sub-region in the country. A distributed lag is incorporated in this and all other research variables i.e.,

$$A(t) = \sum_{1942}^{t-5} A_t + .8A_{t-4} + .6A_{t-3} + .4A_{t-2} + .2A_{t-1}.$$

The most recently conducted research is not fully counted since its full impact will not be realized until 8 to 10 years after investment.

S is cumulated S-type research investment per sub-region. Note that since it enters only in the exponent it does not have a direct effect on productivity but an indirect effect through changing the productivity of A.

RA measures A-type research conducted in other countries which is directed toward crop production in the same geo-climate region.

ZS measures S-type research in other countries which are in the same geo-climate zone.

RY is an index of the yield of food grains per hectare in time period t relative to the 1949-51 average of similar sub-regions outside the country.

The a-priori expectations regarding the signs of the coefficients $a_1, a_2 \ldots a_{10}$ are:

- a_1, the land coefficient, should be positive and approximately one since land is serving as a proxy for left-out inputs, chiefly labor and power.
- a_2, the fertilizer coefficient, should be positive and approximately equal to the share of fertilizer in total costs.
- (a_3+a_4S), the A-type research coefficient should be positive for the mean value of S. a_3 need not be positive if a_4S is large to indicate that indigenous research has contributed to production.
- $a_5+a_6ZS)$, the RA-type research coefficient similarly should be positive, if regional research has contributed to production.
- a_7, the interaction coefficient between indigenous and regional research, should be positive, since indigenous research should complement, that is, raise the productivity of regional research.
- a_8, the coefficient for the squared interaction term may be negative, indicating that when indigenous research is large relative to regional research, it may be a net substitute for the regional research.
- a_9, the coefficient for the regional yield transfer variable, should be positive. The size of the coefficient shows the proportion of yield increases which are transferred between similar sub-regions as a consequence of activities unrelated to research.
- a_{10}, the coefficient for the interaction between regional yields and indigenous research should be negative since the more indigenous A-type activity, the more difficult is direct technology transfer since better alternatives are being discovered.

Table 2 reports regression estimates of the coefficients a_1 through a_{10} for developed countries (regression 1) and developing countries (regression 2). For both regressions, all estimated coefficients have the expected signs and the reported standard errors indicate high levels of statistical significance.[9] The coefficients estimated for the land (a_1) and fertilizer (a_2) variables suggest that these variables are capturing the influence on production of changes in conventional inputs reasonably well.

It is of special interest to note that the terms involving the S-type research activity variables (a_4 and a_6) are positive and significant in both regression sets. This is strong evidence that S-type research is productive through its influence on the productivity of A-type research. The net productivity of A-type research is also positive according to these results.

A further implication of these results is that the results of A-type research are transferred to other sub-regions in the same region and that S-type research results are transferred to other sub-regions in the same zone. That is, A-type research (and indirectly S-type research) is associated with productivity increases in sub-regions other than the region where the research is undertaken. The terms a_7 and a_8 show that indigenous research complements the transferability of regional research. The higher the level of indigenous research (up to a point), the more the country benefits from the research of its ecological neighbors.[10]

The Green Revolution Implications

Much of the literature dealing with the green revolution stresses the role of the International Rice Research Institute (IRRI) and the International Maize and Wheat Improvement Center (CIMMYT) in developing the high yielding dwarf type wheat and rice varieties. In fact, some of the literature leaves the misleading impression that the handful of new varieties released from these centers not only represents the only important new technology to emerge in the developing world, but that adoption of these varieties should be expected throughout all regions. In fact, adoption has been quite limited. The initial set of high-yielding varieties was quickly expanded by new varieties of both wheat and rice released from national research centers. A few of these varieties were developed independently of the work in the international centers,[11] but most represent cases of "knowledge transfer" as discussed earlier, and were developed by crossing local varieties with the international genetic material.

By 1972-73, 34 percent of the wheat acreage of South Asia, the Middle East and North Africa had been planted to "high yielding varieties" as defined by Dalrymple (1973). The comparable figure for rice acreage in Asia was 21 percent. These varieties included both the international center varieties and the varieties discovered by national research centers which represent joint products of the national and international centers.

In regression 3, Table 2, a new variable, HYV, the percentage of area of wheat or rice planted to high-yielding varieties is incorporated into the regression analysis. A squared term and an interaction term with indigenous research are also included. The addition of these new variables contributes to the statistical explanation of productivity gains.

Table 2. Regression Analysis: Cereal Grain Productivity. Dependent Variable: Cereal Grains Production Index
Regressions weighted by area and estimated using Nerlove-Baelestra techniques. "t" ratios in parentheses.

Independent Variables	Developed Countries	Developing Countries	
	87 Crop-Country Combinations 1948-71 2088 Observations	78 Crop-Country Combinations 1948-71 1872 Observations	
	(1)	(2)	(3)
R^2(Adj)	.981	.986	.987
Constant	.565 (10.55)	.026 (.51)	.087 (2.06)
LN(Land) a_1	.965 (199.8)	1.011 (228.7)	1.083 (222.9)
LN(Fert) a_2	.0333 (8.67)	.0318 (6.26)	.0273 (5.38)
LN(A) a_3	.00707 (2.09)	.00231 (.75)	.0021 (.70)
LN(A)*S a_4	.00000404 (1.64)	.0000684 (7.33)	.0000524 (5.44)
LN(RA) a_5	.01611 (2.46)	–.00014 (.05)	–.00231 (.71)
LN(RA)*ZS a_6	.0000639 (12.09)	.000147 (10.56)	.000157 (11.40)
LN(RA)*(A+S) a_7	.0000093 (2.81)	.000095 (5.17)	.00010 (5.08)
LN(RA)*(A+S)^2 a_8	.2306(–9) (1.46)	–.445(–7) (16.06)	–.646(–7) (7.49)
LN(RY) a_9	.1753 (5.38)	.0627 (2.26)	.0026 (.09)
LN(RY)*A a_{10}	–.000215 (10.12)	–.00061 (8.94)	–.00036 (5.07)
HYV a_{11}	–	–	.00574 (2.93)
(HYV)^2 a_{12}	–	–	–.00154 (3.67)
(HYV)*A a_{13}	–	–	.0000144 (5.81)
D Wheat	–.2233 (10.47)	–.018 (1.53)	–.060 (4.67)
D Barley	–.2777 (14.29)	–.081 (4.69)	–.094 (5.46)
D Rice	–.3455 (12.57)	–.097 (7.29)	–.1164 (8.81)

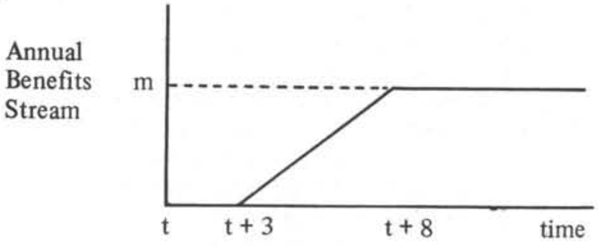
The negative coefficient estimated for the HYV^2 term is evidence for the technology specificity of the high yielding varieties. It shows that as the percentage of acreage planted to HYV's increases, the marginal effect on production decreases. The contribution of the HYV's to production is, however, primarily based on indigenous research capability as indicated by the positive and statistically significant coefficient on the interaction term, HYV*A. In those countries lacking the capability for A-type research (and there are several) the contribution of the HYV's diminishes to zero at less than 20 percent adoption. In the typical developing country the level of A-type research is sufficient to spread the green revolution over 60 percent of the wheat area and 80 percent of the rice area before technology specificity reduces the production impact to zero. And with anything approaching optimal capability for A-type research, the green revolution will be spread over all acreage. The distinction between these particular high yielding varieties will then become more and more arbitrary. The green revolution will have become part of the normal, more evolutionary pattern of technology discovery.[12]

The Economic Implications

It is possible to make several interesting computations based on these regression results. The reader should note that these computations are based on estimates which are subject to error. However, the statistical aspects of the estimates indicate that the errors are relatively small.

The computations reported in Table 3 are based on the following: suppose an additional investment of $1000 is made at time t. What is the expected net gain in production measured in dollars resulting from the investment and when is it realized? The timing of the expected benefits is shown in Figure 2.

Fig. 2



An investment in time t will not result in any discoveries actually utilized by producers until 2 to 3 years after investment. The expected production will then rise to a maximum of m dollars, 8 to 10 years after investment. The levels reported in Table 3 are the estimated maximum levels to which production increases realized annually will rise.

Table 3. Estimated Marginal Benefit Streams Associated with Research Investment Devoted to Cereal Grains Improvement.

Estimated levels (in 1973 dollars) to which benefits streams associated with a one thousand dollar research investment will rise eight to ten years after initial investment.

	Research Investment in Developed Countries		Research Investment in Developing Countries	
	A-type	S-type	A-type	S-type
Part 1 Appropriated by investing country				
(a) direct contribution	630	12,300	3,710	35,600
(b) through complementarity with research in other countries	1,620	1,620	7,200	7,200
(c) Total appropriable	2,250	13,920	10,910	42,800
Part 2 Contributed to countries other than investing country	5,150	17,000	49,000	37,300
Total Benefit Stream Realized From an International Perspective (Part 1 + Part 2)	7,400	30,920	59,910	80,100
Part 3 Benefits realized by a typical country from research investment by other countries in similar climate zones (or regions)				
(a) with average indigenous research capability	8,580	520	55,000	1,700
(b) with no indigenous capability	4,560	520	1,700	1,700

Notes:

1. All computations made from regressions (1) and (2) in Table 2.
2. Computations based on mean values of variables in the derivatives from the two data sets. The derivative is in terms of the effect on production of a change in the knowledge stock. The knowledge stock is converted from publications to dollars based on the data in Evenson and Kislev, Chapter 2, Table 2.4.
3. Cereal grain product is valued at $80 per metric ton (approximate 1973 prices).
4. The distinction between 1a and 1b is made on the basis of the coefficients on LN(A) (or LN(A)*S) and LN(RA)*(A+S) and $LN(RA)*(A+S)^2$ in Table 2. The latter terms are viewed at transfer acceleration terms.
5. Contributions to other countries are computed as 3(a) times the average number of other countries in similar regions for A (.6 developed countries, .9 in developing countries), and zones for S (33 for developed countries, 23 for developing countries).
6. Benefits realized from other countries are computed as the marginal products of RA and ZS. 3(b) is computed setting (A+S) = 0.

They represent the amount of real economic "growth" or production which can be purchased for a $1000 investment.[13]

Part 1 of the table shows the estimated "appropriable" benefits which can be purchased by investing in A-type and S-type research. The estimates are based on the coefficients of the A and S variables in regressions (2) and (3) in Table 2.[14] The average costs of producing a publication are based on Kislev and Evenson (1973).[15] These benefits are captured by the "typical" investing country. A distinction is made between the direct contribution of the research (from a_3 and a_4) and the complementarity with regional research (from a_7 and a_8).

Part 2 of the table reports the estimated contribution to other countries which are in a position to benefit from the research investment. This is computed for a "typical" country (based on the RA and ZS coefficients) and is not very meaningful for individual countries. It is, however, important from an international perspective because the sum of the appropriated and the contributed benefit represents the total payoff of the investment. If the benefits rise to only $2,300, the "internal rate of return" realized on the investment is 15 percent, a rate that is realized on relatively few projects. Thus the amount of growth that can be purchased through investment in research is estimated to be several times greater than is possible with most investments.

The higher estimated benefits streams associated with investment in the developing countries should not be surprising. It does not reflect high productivity per se. In fact, the developing country scientists produce significantly fewer publications per scientist than the scientist in the developed countries.[16] The nature of the specification is such that diminishing returns to added research are expected to hold. Consequently countries that underinvest in research will realize high rates of return even if the research is poorly organized.

The implications for investment in S-type research are important. That the developing country data should show that it is extraordinarily productive, indeed the best investment bargain, does not square with the perspective of many. The policy literature regarding agricultural research in the developing countries places great stress on the "adaptive" A-type research. These results indicate that policy makers are persisting in making the same errors of an earlier period when the emphasis was on direct technology transfer. The advocates of A-type research emphasis are counting on the easy transfer of scientific knowledge. The high returns to S-type research indicate that this knowledge is not easily transferred.

Part 3 of the table shows the role of indigenous research capability in terms of its effect on the benefits a country can realize if another country in a similar geo-climate region (or zone for S-type research) invests $1,000 in A-type or S-type research. The benefits are great for both developed and developing countries. If a country fails to develop a research capability ($A + S = 0$), 3(b) shows that it can expect appreciable "spill-over" from other countries if it is a developed country, but very little if it is a developing country. A policy of "borrowing technology from neighbors" just doesn't work. Even if the neighboring country is considerate enough to invest in research, little of it can be borrowed unless an indigenous discovery capability exists.

Perspective for the World Food Problem

The finding that science matters, and that the building of research capability offers developing countries an opportunity to purchase a tremendous amount of growth does not necessarily mean that one can be optimistic about future food-production possibilities. The agricultural sectors of most developing countries have systematically been discriminated against in allocation of public funds. Even India, which has one of the best agricultural research systems in the developing world, allocates only a tiny fraction of its budget to research. Also, development agencies have not had really aggressive programs to aid countries in the building of research capability. They have at times provided significant funding for research, as in the 1950s, when perhaps half of the investment in developing country research was provided by aid from developed countries. But today, less than 5 percent of the funding for indigenous research systems is provided through aid.[17]

Annual investment in real terms for all developing countries is estimated to be $236 million in 1970, a significant expansion over the $77 million invested in 1958 (Evenson, 1973). The time lag between investment and benefits means that the research investment of the late 1950s and early 1960s has determined productivity performance in the late 1960s and early 1970s. By 1980, the stock of research knowledge of relevance to agricultural production will be 3- to 4- times the magnitude of the stock that has mattered in the past few years.

The initial impact of the green revolution has now been realized and is unlikely to be repeated. The importance of the international centers now lies in their role in facilitating the transfer of scientific knowledge to and between developing countries. It is unfortunately a role that they have not opted to stress, maintaining instead that their comparative advantage continues to be with A-type research (utilizing researchers with S-type training and knowledge—an effective combination). Nonetheless, the centers have added an important new dimension to developing country research.

Thus, the prognosis is mixed. A number of countries are aggressively moving toward expansion in quantity and quality of technology discovery capability. They are backing up research activity with aggressive extension and rural schooling investments. Even in cases where population growth is relatively high, one can be quite optimistic regarding food production. It is quite likely that production per capita in many, perhaps most, of the developing countries will continue to increase over the next ten years.

Many countries, however, are not oriented toward the improvement of agriculture. The agricultural sector has not been viewed as a source of growth and only the most rudimentary institutions to achieve growth have been built.

These countries have in many cases also been subjected to great political instability. It is very likely that the rapid population growth now being experienced in these countries will be translated into declining real incomes. Their inability to produce their own improved technology unfortunately means that they will benefit little from improved technology development elsewhere.

It is difficult to say just how many countries fall into this category. The total population involved is certainly cause for concern. It will be a great challenge to international aid agencies to provide funding and technical support to initiate technology improvement activities and to build the capacity to produce sustained improvements in food production in these countries.

FOOTNOTES

[1] See Bhagavan; 1973, Sterra, 1973, Nossiter, 1973 and New York Times, 1973 for statements reflecting the pessimistic viewpoint.

[2] A substantial literature on models of optimal growth exists, and while it does deal with the role of factor prices in guiding technology discovery which are of most value, it has little to offer regarding the way discoveries are made.

[3] The distinction between techniques and technology as terms are used in this paper is that techniques are actually utilized by producers. Technology encompasses techniques in use plus those which are known and which may potentially be used.

[4] See Stigler, 1961, for an application of the search concept to economic activity.

[5] For a discussion of the responsiveness of research institutions to perceived values of discoveries see Hayami and Ruttan, 1973 and Schultz, 1971.

[6] These climate zones are similar to the more conventional Koopen classification, Papadakis, however, devised his system to classify agricultural production potential.

[7] In the regression analysis dummy variables for each crop provide a control for systematic differences between crops in this regard.

[8] Evenson & Kislev, 1974, Chapter 2, presents a detailed discussion of available data on investment in agricultural research and extension. In general, the data showing research expenditures or numbers of scientists show the same pattern revealed in Table 1.

[9] A simple rule for judging statistical validity of the coefficients is that a "t" ratio of 2 or greater indicates that the coefficient is highly significant. This simply means that given the observed random errors in the data the "probability" that the "true" coefficient is zero or less (greater of the coefficient should be negative) is very low (.05 or less).

[10] See the estimated a_9.

[11] The 1972-73 data have been made available to me by Dana Dalrymple.

[12] See Evenson, 1974a, 1974b, for a further discussion of the green revolution.

[13] Note that these are annual streams of benefits. The 10,910 dollar stream produced by a 1,000 dollar in investment in A-type research in developing countries is realized annually, not just in one year. The investment can be viewed rather like purchasing an annuity.

[14] Regression 2 is more appropriate for this purpose than regression 3 since the green revolution regression captures the relatively short-term HYV effects. The relationship in regression 2 is a more stable long run relationship.

[15] In 1973 dollars the average cost of a publication, as defined in this study, in developed countries was $140,000. In developing countries, the cost was $125,000. The differences in cost per scientist is much greater than this. However, the lower scientist productivity (in terms of publications per scientist) almost offset the scientist cost differences. See Evenson & Kislev, 1974.

[16] See Evenson & Kislev (1974), Chapter 2.

[17] See Evenson, 1973, for an estimate.

REFERENCES

Bhagavan, M.R. et.al. *The Death of the Green Revolution,* Haslemere Declaration Group, London, 1973.

Dalrymple, D.G. *Imports and Planting of High Yielding Varieties of Wheat and Rice in the Less Developed Countries.* Foreign Economic Development Report-14. Washington, D.C., USDA, Foreigh Economic Development Service, 1972.

Evenson, R.E., 1969, "Economic Aspects of the Organization of Agricultural Research," in W.L. Fishel, ed., *Resource Allocation in Agricultural Research,* University of Minnesota Press.

Evenson, R.E., 1973, "National Agricultural Research Systems: A Survey Paper," prepared for the Consultative Group on International Agricultural Research, World Bank.

Evenson, R.E., 1974a, "The Green Revolution in Recent Development Experience, *American Journal of Agricultural Economics,* May.

Evenson, R.E., 1974b, "Consequences of the Green Revolution," Proceedings VI Pacific Trade Conference.

Evenson, R.E. and Yoav Kislev, 1973, "Research and Productivity in Wheat and Maize," *Journal of Political Economy,* (forthcoming).

Evenson, R.E. and Yoav Kislev, 1974, *Agricultural Research and Productivity,* Economic Growth Center, Yale University Press (forthcoming).

Evenson, R.E. and Yoav Kislev, 1971, "Investment in Agricultural Research and Extension: A Survey of International Data," Economic Growth Center, Yale University, Center Discussion Paper No. 124 (mimeo).

New York Times, "Vanishing Glut," editorial, Jan. 2, 1973.

Nossiter, B. "The Death of Slogan," *Washington Post,* April 18, 1973.

Papadakis, J. 1966, *Agricultural Climates of the World,* Buenos Aires.

Ruttan, V. and Y. Hayami, 1971, *Agricultural Development: An International Perspective,* Baltimore and London: Johns Hopkins Press.

Schultz, T.W. "The Allocation of Resources to Research," in W.L. Fishel, *Resource Allocation in Agricultural Research,* University of Minnesota Press, 1971.

Sterra, J., "The Green Revolution Hasn't Ended Hunger," *New York Times,* April 15, 1973.