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The Evenson-Kislev "Research As Search" Model and the Green Revolution

Robert E. EVENSON† and Yoav KISLEV‡

ABSTRACT. – This paper applies the methodology originally developed by Zvi Griliches in his studies of Hybrid Corn technology to the Green Revolution. The Green Revolution in developing countries – i.e., the production and diffusion of "Modern Varieties" (MVs) of crops – had much in common with the development of Hybrid Corn varieties. In his original work, GRILICHES [1957] noted that the hybridization method was the "invention of a method of invention". The conversion of this method into actual inventions suited to a particular location required the building of plant breeding programs in that location, selecting varieties for that location. This conversion principle applied to the Green Revolution as well. This paper applies the "Research as Search" model of EVENSON and KISLEV [1976] to the production of MVs in the Green Revolution.

La Révolution Verte : leçons des céréales hybrides

RÉSUMÉ. – Cet article applique la méthode initialement développée par Zvi Griliches dans ses études sur la technique d'hybridation et la Révolution Verte. La Révolution Verte dans les pays développés (i.e. la production et la diffusion de variétés modernes de produits agricoles) a été très liée au développement des variétés hybrides. Dans son travail initial, GRILICHES [1957] note que la méthode d'hybridation a été « l'invention d'une méthode d'invention ». La transformation de cette technique en inventions réelles est liée à une localisation spécifique, nécessite la mise en place de programmes de reproduction des plantes à cet endroit ainsi que la sélection de variétés adaptées à cette localisation. Ce principe de transformation s'applique à la Révolution Verte. Cet article applique le modèle de EVENSON et KISLEV [1976] "Research as Search" à la production de nouvelles variétés lors de la Révolution Verte.

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1 Introduction

Zvi Griliches [1957], in his study of hybrid corn, provided us with several tools for the analysis of technological change in agriculture. He noted first that the hybrid methodology was the "invention of a method of invention". The hybridization methodology thus did not lead to usable inventions (in the form of hybrid corn varieties) *per se*. Actual inventions required the building of plant breeding programs in each major agro-ecology zone (AEZ).

In this paper we apply the analytics of the original Griliches hybrid corn study to the Green Revolution. We incorporate a study of the "germplasmic" contribution to plant breeding programs in National Agricultural Research Systems (NARS) by the plant breeding programs in the International Agricultural Research Centers (IARCs).

The Green Revolution is the term used to describe the production and the diffusion of "High Yielding" or "Modern Varieties" (MVs) of several different crop species in developing countries (Evenson and Gollin [2003]). The earliest MVs were wheat and rice MVs introduced to farmers in Latin America and Asia in the mid 1960s. In some regions, these MVs were adopted rapidly by farmers (approximating the rapid diffusion rates for hybrid corn in Iowa). But, as with hybrid corn, origin dates for MV adoption varied considerably by agroeconomic zone.

This variation in origin date is well illustrated for MVs of maize (corn)[1]. CIMMYT, the International Center for Wheat and Maize Improvement with a mandate for maize improvement, first concentrated on developing improved "open-pollinated varieties" (OPVs). The breeding methods for OPVs apply to most Green Revolution varieties. They entail strategic crossing of parental lines and subsequent selection for phenotypic plant traits. Hybridization requires multi-generational "inbreeding" followed by crossing of inbred lines to achieve a "heterosis-based" yield increase. This heterosis effect is not realized in the subsequent generation, so farmers cannot save their own seed from hybrid crops. Once improved OPVs were achieved, they could be hybridized. Griliches noted that farmers in Iowa had access to hybrid corn varieties 20 years earlier than did farmers in Alabama. Farmers in West Africa did not have access to hybrid corn until 70 years after farmers in Iowa had access and farmers in Central Africa still do not have hybrid corn varieties.

The IARC-NARS breeding programs are public sector programs. The IARC programs have been supported by a consortium of donors, the Consultative Group for International Agricultural Research (CGIAR). Ten IARCs have crop improvement mandates for 15 major food crops and a number of vegetable crops.

In this paper, we analyze the production of MVs. We utilize the Evenson-Kislev [1976] model of "research as search" to analyze IARC-NARS complementarity in MV production.

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[1] Readers should note that the term "corn" has been applied to maize and to wheat. The "Corn Laws" in Britain actually refer to wheat.

2 The production of MVs

Table 1 documents the production of MVs (measured as the number of varieties released by domestic release boards) by period and region for ten major food crops. Thirty-six percent of these MVs were based on an IARC cross (IX) and an additional 20 percent were based on a NARS cross with an IARC crossed parent. This is impressive because the IARC proportion of agricultural scientists is less than five percent of total IARC-NARS scientists. The IARC ancestry proportions are highest for the regions with weakest NARS programs: the Middle East-North Africa and Sub-Saharan Africa regions.

Following the search model developed by STIGLER [1961], EVENSON and KISLEV [1976] suggested the representation of research as a search process. The original work was applied to search for a single "trait" or characteristic. The model and its extensions are reviewed in this section and further developments regarding the "adaptive" or "recharge" features of the model are also developed. An empirical application follows.

2.1 The single period-single trait model

The single period, single trait model stresses plant traits sought by plant breeders. Plant breeders have two alternative search strategies in their research programs. The first of these is the search for "quantitative" plant traits governing yields. Quantitative traits are controlled by multiple genes (or genetic alleles) and require complex strategies for crossing parental materials and selecting improved cultivars. The second is the search for "qualitative" traits such as host plant resistance to the tungro virus in rice. Typically, qualitative traits are controlled by a single gene. Conventional breeding programs use "back crossing" strategies to incorporate these traits (modern biotechnology methods are also used to genetically engineer these traits)[2].

Both breeding strategies rely on searching for genetically controlled traits in collections of crop genetic resources, which include "landraces" of the cultivated species (distinct types selected by farmers over centuries and diffused across different ecosystems), "wild" or uncultivated species and related plants that might be combined. The systematic combining of landraces into breeding lines is termed "pre-breeding"[3].

Consider the original EVENSON-KISLEV [1976] model: Existing breeders' techniques and breeders' collections of genetic resources determine a distribution of potential varieties indexed by their economic value, x. Suppose this distribution to be exponential:

$$f(X) = \lambda e^{-\lambda(x-\theta)} \quad \theta \leq x \tag{1}$$

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[2] Backcrossing strategies entail crossing parental plants with their progeny to eliminate unwanted genetic combinations.

[3] The pre-breeding activities of the International Agricultural Research Center are an important part of the recharge mechanism (see EVENSON and GOLLIN [2003b]).

TABLE 1

Average Annual Varietal Releases by Crop and Region 1965-1998.

	Average Annual Releases							1965-1998 IARC Content**			
Crop	1965-70	1971-75	1976-80	1981-85	1986-90	1991-95	1996-98*	IX	IP	IA	IN
Wheat	40.8	54.2	58.0	75.6	81.2	79.3	(79.3)	.49	.29	.08	.14
Rice	19.2	35.2	43.8	50.8	57.8	54.8	58.5	.20	.25	.07	.48
Maize	13.4	16.6	21.6	43.4	52.7	108.3	71.3	.28	.15	.04	.53
Sorghum	6.9	7.2	9.6	10.6	12.2	17.6	14.3	.16	.07	.06	.71
Millets	0.8	0.4	1.8	5.0	4.8	6.0	9.7	.15	.41	.09	.35
Barley	0.0	0.0	0.0	2.8	8.2	5.6	7.3	.49	.20	.01	.30
Lentils	0.0	0.0	0.0	1.8	1.8	3.9	(3.9)	.54	.05	.01	.40
Beans	4.0	7.0	12.0	18.5	18.0	43.0	(43.0)	.72	.05	.01	.19
Cassava	0.0	1.0	2.0	15.8	9.8	13.6	(13.6)	.53	.15	.01	.31
Potatoes	2.0	10.4	13.0	15.9	18.9	19.6	(19.6)	.17	.06	.02	.75
All Crops											
Latin America	37.8	55.9	65.9	92.5	116.2	177.3	139.2	.39	.14	.04	.43
Asia	27.2	59.6	66.8	86.3	76.7	81.2	79.9	.18	.29	.10	.43
Middle East-North Africa	4.4	8.0	10.2	12.2	28.4	30.5	82.2	.62	.22	.04	.12
Sub-Saharan Africa	17.7	18.0	23.0	43.2	46.2	50.1	55.2	.45	.21	.07	.27
All Regions	87.1	132.0	161.8	240.2	265.8	351.7	320.5	.36	.20	.06	.38

** Numbers in parentheses are simple repetition of 1991-95 rates because of insufficient data.*

*** IX: Varieties based on crosses from international agricultural research centers; IP: Varieties based on crosses from national research systems with at least one parent from an international center; IA, Varieties based on crosses from national systems with at least one non-Parent ancestor from an international center; IN: Varieties based on crosses from national systems with no international ancestors.*

Source: EVENSON and GOLLIN [2003].

The cumulative distribution is:

$$F(X) = 1 - e^{-\lambda(x-\theta)} \tag{2}$$

with mean and variance

$$E(X) = \theta + \frac{1}{\lambda} \tag{3}$$

$$Var(X) = \frac{1}{\lambda^2} \tag{4}$$

The cumulative distribution of the largest value of x, denoted by z, from a sample of size n is the "order statistic":

$$H_n(z) = [1 - e^{-\lambda(z-\theta)}]^n \tag{5}$$

and the probability density function for z is:

$$h_n(z) = \lambda n[1 - e^{-(z-\theta)}]^{n-1} e^{-\lambda(z-\theta)} \tag{6}$$

The expected value and variance of z are

$$E_n(z) = \theta + \frac{1}{\lambda}\sum_{i=1}^{n}\frac{1}{i} \tag{7}$$

$$Var_n(z) = \frac{1}{\lambda^2}\sum_{i=1}^{n}\frac{1}{i^2} \tag{8}$$

EVENSON and KISLEV [1976] discuss the applicability of expression (7) to plant breeding research. Basically (7) can be thought of as the breeding production function. Expression (9) is a reasonable approximation of (7) for any symmetric distribution $f(x)$ including the uniform distribution (KORTUM [1997]) and the normal distribution:

$$E_n(z) = \theta + B\ln(n) \tag{9}$$

The marginal product of breeding effort is simply:

$$\frac{\partial E_n}{\partial n} = \frac{B}{n} \tag{10}$$

When a measure of the economic units, V, over which z applies is defined (e.g., the value of production in a specific ecosystem), the value of the marginal product can be computed and set equal to the marginal cost of search to solve for optimal *n*:

$$BV/n = MC(n) \tag{11}$$

2.2 Multiple traits

For two or more traits, each can be characterized by (9) with different parameters:

$$\begin{aligned} E_n(z_1) &= \theta_1 + B_1 \ln(n_1) \\ E_n(z_2) &= \theta_2 + B_2 \ln(n_2) \\ E_n(z_3) &= \theta_3 + B_3 \ln(n_3) \end{aligned} \tag{12}$$

When these traits are qualitative traits, breeders typically search for them independently because there are techniques enabling the breeders to incorporate only the single trait in a cultivar. Thus, even if traits are highly correlated, the breeder will typically search independently for them[4].

Set

$$n_1 + n_2 + ... n_n = n^* \tag{13}$$

Equation (13) defines a transformation function (in expected value terms) that can be regarded as a single period Innovation Possibilities Frontier (IPF). The standard induced innovation model predicts that, if breeders are economically motivated, optimal traits will be chosen as a function of prices or values given the IPF for *n**.

2.3 Sequential search without recharge

In practice, we observe multiple period, sequential research in plant breeding programs. There are two reasons for this. The first is that experiments have a natural phasing and evaluation property. In plant breeding programs this entails "selection under stress". The breeder makes *n* crosses in each period. The F_1 generation from each cross is evaluated. For some crosses this evaluation may call for termination of selection. For other crosses, further selection is justified. This selection is typically undertaken under stress to better identify the traits. For example, when selecting for host plant resistance to a disease, F_1 plants are inoculated with the organism causing the disease.

This process of selection is sequential and proceeds for several generations, each requiring an evaluation before the next generation strategy can be developed. As

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[4] This independent search for traits is dictated by the fact that traits have different genetic sources.

these evaluations proceed, more lines are dropped as unpromising and more potential crosses are revealed to be promising.

2.4 Sequential search with recharge

Plant breeding programs are associated with several types of recharge mechanisms. These include:

1. Genetic resource collection and evaluation programs. These programs are designed to discover unidentified sources of genetic contributions.
2. Pre-breeding programs where landrace materials are systematically combined into potential breeding lines by specialized research programs. These programs do not seek to develop "final products" or new cultivars. Instead they seek to evaluate and produce "advanced lines" that are then used by final product inventors.
3. Wide-crossing programs where techniques for inter-specific combinations of genetic resources (between related species) are utilized. This expands the scope of the original materials that can be utilized in breeding programs.

These programs are "pre-invention science" programs. They provide "recharge" to the invention distributions by shifting both the mean and the right-hand tail of the invention search distribution to the right. The actual mechanism of recharge is often in the form of varieties that serve as parents in the recharged invention distribution.

Suppose that the shifters of the varietal discovery function (9) are international germplasm G_I, and domestic germplasm, G_n. Then we write the germplasm enhanced varietal discovery function as:

$$V_N = a_0 + d_1 \ln(B_n) + d_2 \ln(B_n) G_I + d_3 \ln(B_N) G_N \tag{14}$$

Equation (14) specifies the contribution of international germplasm and cumulated domestic germplasm to national breeding programs[5].

2.5 Location specificity and recharge

Foreign germplasm, G_I, may take the form of varieties suited for direct release in the recipient country. In this case they could be directly substitutable for domestic innovations (varieties). In the empirical section below, a subset of the varieties crossed in an IARC program are treated as germplasm for national programs. We measure potential recharge value by whether the internationally bred variety was released in a given country[6].

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[5] Note that for inventors receiving recharge, the recharge elements shift the invention distribution linearly. The diminishing returns to pre-invention or recharge activities themselves are not incorporated into the recharge recipients' invention functions.

[6] GOLLIN and EVENSON [1997] provide data on varietal releases by IARC and NARS programs for rice. Most varieties crossed at IRRI were released in several countries. Only 6 percent of the NARS crossed varieties were released in a second country.

2.6 Applying the search model to green revolution MVs

The research as search model outlined earlier provides a basis for testing the impact of imported germplasm on national breeding programs. The "breeding with recharge" function imposes a specific functional form for the germplasm impact. Estimates of the model are based on national program data for three periods, 1965-75, 1976-85 and 1986-96, for varietal releases in wheat, rice, maize, beans, and potatoes.

Equation (14) specifies the search model process by which international research affects national breeding programs. International research plays a complementary role to domestic breeding efforts. Complementarity encourages local investment in research. But international research may also compete with local breeding effort, when varieties developed in the international centers are released in the individual countries. Competition may discourage local breeding effort.

The estimation framework calls for two endogenous variables, V_N, the number of varieties produced by a national program and B_N, the number of plant breeders in the national program. The specification of the two equations are:

$$(15)\qquad V_N = a_0 + a_1 \ln(B_N) + a_2 \ln(B_N)G_I + a_3 \ln(B_N)G_N + DC + DP$$

(16)

$$\ln(B_N) = b_0 + b_1 \ln(G_I) + b_2 \ln(G_N) + b_3 \ln(HA) + b_4 \ln(RPopden) + b_5 \ln(GDP/c) + b_6 \ln(G_I)\ln(HA) + b_7 \ln(G_I)\ln(RPopden) + b_8 \ln(G_I)\ln(GDP/c) + DTC + DC + DP$$

The G_I and G_N variables are shifters, they are not part of the current national search and are not subject to diminishing returns as is B_N. They are also taken here as exogenous; that is, (except indirectly) germplasm coming from international centers affects national breeding productivity, but national research does not produce germplasm for the international centers. Dummies: technology DTC, climate DC, period DP.

Table 2 reports variable definitions and means for variables as defined with reference to equations (15) and (16). Data are for 3 periods, 1965-75, 1976-85 and 1986-96. In parentheses, number of observations.

V_N is the number of varietal releases in a country based on crosses made in national programs over the period.

B_N is the number of scientists engaged in research on the crop at the beginning of the period. The variable B_N was estimated in two stages. First the total number of senior agricultural scientists for the period and country was computed from the ISNAR database (PARDEY and ROSEBOOM [1990]). In the second stage, the number of scientists in a country was allocated to crops in the following way. A search was conducted in the FAO Agrostat database for publications on plant breeding and related activities by crop; a similar search was conducted on social science research, animal and pasture research and other fields of agricultural science. Publication shares for plant breeding on the crops in question were then computed for each country. These shares were multiplied by the ISNAR scientist data to obtain our measure of crop level B_N.

TABLE 2

Variable Definitions: Means by Crop – 3 Periods 1965-75, 1976-85 and 1986-96.

Variable	Definitions	Wheat (66)	Rice (54)	Maize (32)	Beans (45)	Potatoes (51)
I. Endogenous Variables						
B_N	Number of scientist man years in NARS programs	298	206	126	25.6	61.1
V_N	Number of NARS crossed varietal releases	30.6	19.5	10.5	4.36	11.6
II. Exogenous Variables						
G_I	International Germplasm Stocks: Cumulated number of IARC crossed varieties released in the countries	19.0	6.31	1.88	4.09	9.98
G_N	National Germplasm Stocks: Cumulated NARS crossed varietal releases (V_N) in previous periods	21.1	15.4	6.15	1.06	6.61
HA	Hectares (000) planted to the crop at the beginning of the period	2,847	4,613	244	377	1,470
RIPOPDEN	Population Density at the beginning of the period, Rural Population/area in crops and pasture (FAO)	256	411	523	268	230
GDP/c	GDP *per capita* in US dollars beginning of period, World Bank Atlas Method (World Bank Tables)	2,784	2,820	1,954	2,577	3,410
Climate	Climate class indicators, from EVENSON [2000] (See Appendix 21.2 of EVENSON [2003])					
1		.26	.39	.64	.62	.58
2		.40	.22	.27	.25	.24
3		.31	.16	.18	.19	.24
4		.31	.06	0	0	.06
5		.18	.11	.18	.13	.12
6		.09	.06	0	.06	.06

G_I is measured as the cumulated number of international crosses released as varieties in the country. This definition of germplasmic input attempts to take account of the fact that only a subset of internationally crossed material is relevant in a given country. Crosses made at an international center and subsequently released in an individual country clearly indicate that the research done in the center was relevant for the specific conditions of the country.

G_N is measured as the cumulative nationally bred crosses released in the country at the beginning of the period.

Table 3 reports 2SLS estimates of the varietal production function (15) for each crop and for pooled crops. 3SLS estimates for pooled crops are also reported. Coefficients for climate and period dummies are not reported.

Table 4 reports 2SLS estimates of the breeders investment function (16). Coefficients for climate, technology class and period dummy variables are not reported. 3SLS estimates for pooled crops are reported.

TABLE 3

Estimates: Variety Production in the National Agricultural Research Systems Dependent Variable: Varieties Releases in the National Systems, V_N

Independent Variables	2SLS (Second Stage)						3SLS
	Wheat	Rice	Maize	Beans	Potatoes	Pooled	Pooled
	4.813	11.926	6.742	1.287	2.490	4.918	7.702
Ln (B_N)	(1.54)	(2.32)	(2.79)	(.71)	(.69)	(2.94)	3.26
	.0966	.1443	.8919	.3496	.3314	.1985	.2395
Ln (B_N) × G_I	(1.85)	(1.53)	(4.21)	(4.55)	(6.24)	(6.61)	(6.29)
	.0141	.0835	.0236	-.00015	.0427	.0600	.0146
Ln (B_N) × G_N	(.58)	(3.45)	(.72)	(.05)	(1.47)	(4.50)	.73
D Beans						-2.32	1.69
D Rice						-3.69	-9.48*
D Potatoes						-6.78	-8.42*
D Maize						-.35	2.09
# Obs	66	54	32	45	51	248	248
R^2	.711	.593	.849	.742	.741	.533	.596

2.7 Implications for productivity of the national agricultural research systems

The recharge role of international programs in the Green Revolution was very important to the production of modern varieties. Table 5 reports elasticities for independent variables on the production of modern varieties in the national programs. These elasticities show:

a. That national breeding resources (B_N) are subject to diminishing returns with elasticities well below one.

b. That international germplasm (G_I) has an important productivity enhancing impact for all crops.

c. That national germplasm stocks (G_N) also have a productivity impact, but of smaller magnitude than international germplasm.

TABLE 4

Estimates: Investment in Development of varieties in the National Agricultural Research Systems
Dependent Variable: ln(BN)

Independent Variables	2SLS (Second Stage)												3SLS Pooled	
	Wheat		Rice		Maize		Beans		Potatoes		Pooled			
ln (G_I)	-1.82	(1.35)	1.164	(.56)	.1884	(2.40)	-2.921	(1.13)	-1.074	(.37)	-2.061	(2.36)	-2.041	(2.56)
ln (G_N)	-0.87	(.85)	.150	(1.33)	.251	(1.04)	-.018	(.09)	.013	.09	-.03	(.43)	-.055	(.97)
ln (*HA*)	.495	(3.45)	.745	(4.06)	.581	(1.83)	.533	(2.08)	.390	(2.19)	.347	(6.03)	.332	(6.24)
ln (*RPopden*)	1.341	(5.88)	.708	(2.44)	.313	(.52)	.281	(.63)	-.022	(.05)	.367	(2.39)	.534	(2.39)
ln (GDP/C)	-.339	(.74)	.863	(2.01)	-2.76	(.61)	-.275	(.86)	1.065	(1.73)	.117	(.76)	.125	(.89)
ln (G_I) × ln (HA)	.108	(1.87)	.029	(.46)	.170	(1.02)	.066	(.67)	.069	(.84)	.103	(4.39)	.122	(5.63)
ln (G_I) × ln (*Popden*)	-.095	(.75)	.237	(1.59)	.971	(1.57)	.122	(.63)	.149	(.69)	.112	(1.65)	.094	(1.52)
ln (G_I) × ln (GDP/C)	.112	(.78)	-.015	.10	1.409	(2.16)	(.150)	(.17)	-.092	(.34)	.007	(.09)	-.022	(.32)
# Observations	66		54		32		45		51		248		248	
R^2	.711		.593		.849		.742		.741		.533		.496	
F	22.9		13.16		6.36		5.70		6.82		29.5			

d. That the sum of the production elasticities is approximately one or greater (except for wheat), indicating that the recharged national breeding programs were not subject to diminishing returns.

TABLE 5

Modern Varieties Production Elasticities

	2SLS (Second Stage)						
Independent Variables	Wheat	Rice	Maize	Beans	Potatoes	Pooled	3SLS Pooled
B_N	.23	.72	.81	.62	.52	.45	.60
G_I	.23	.20	.50	.73	.92	.38	.46
G_N	.04	.28	.04	0	.08	.14	.04
Sum	.50	1.20	1.35	1.35	1.52	.97	1.10

2.8 Implications for investment in national systems of agricultural research

International germplasm has two effects on investment in the national programs. One is the complementary effect reflected in Table 3 and 4. The second is a substitution effect associated with the fact that international centers produce varieties that potentially compete with varieties produced by the national systems.

Table 6 reports elasticities for the investment equation (16).

G_I elasticities are evaluated at median levels of population density hectares planted and GDP/c.

The elasticities show:

a. That investment in the national programs responds positively to hectares planted to the crop, but with elasticities below one. This is indicating that there are significant scale economics to plant breeding programs.

b. That investment in the national programs responds positively to rural population density. For the pooled estimates the *RPopden* elasticities are approximately 0.5, similarly to those for hectares. This population density effect is reflecting concern with land scarcity. This "Boserup effect" (BOSERUP [1965]) is quite strong. Countries with low population densities perceive that they can expand production by expanding area cropped and they do not invest in plant breeding capacity.

c. Income (GDP/c) elasticities are low and not statistically significant.

d. International germplasm (G_I) elasticities evaluated at median rural population densities, hectares planted and GDP/capita are positive.

e. National germplasm elasticities are not significant.

These findings indicate that national programs with large acreages and high population densities are responding positively to the complementary impact of

TABLE 6

Elasticities: Investment in Development of Varieties in the National Agricultural Research Systems

Independent Variables	2SLS (Second Stage)						3SLS Pooled
	Wheat	Rice	Maize	Beans	Potatoes	Pooled	
HA	.75	.78	.67	.59	.51	.50	.52
	(.000)	(.000)	(.026)	(.026)	(.007)	(.000)	(.000)
RPopden	1.12	.99	.84	.39	.24	.49	.47
	(.000)	044	(.005)	(.279)	(.704)	(.000)	(.000)
GDP/C	-.08	.84	.49	-.14	.80	.13	.09
	(5.26)	(.641)	(.032)	(.653)	(.022)	(.319)	(.330)
G_I*	.10	3.08	.41	.10	.09	.21	.40
P Values	(.143)	(.612)	(.028)	(.255)	(.704)	(.015)	(.009)
G_N	-.087	(.150)	(.251)	-.018	.013	-.03	-.066
P Values	(.40)	(.601)	(.315)	.93	(.920)	(.67)	(.33)

P values; sum of coefficients in parentheses

** Evaluated at median values of interacting variables.*

internationally bred germplasm. For countries with small acreages and low population densities, the substitution effect outweighs the complementary effect. When weighted by actual hectares, population densities, and GDP/capita, these estimates show that the weighted net elasticity is approximately 0.18. IARC programs thus stimulate NARS investments.

3 Returns to research

In GRILICHES' original work [1958], methods for estimating benefits for a supply function shift were developed. Benefits estimates were based on changes in consumers' surplus plus changes in producers' surplus. For hybrid corn development, a cost (of R&D, both public and private) stream was assessed for the period 1900 to 1957. Annual benefits estimates were based on experiment station and field plot comparisons between OPV and hybrid yields. With measure of adoption rates, an annual benefits stream for 1900 to 1957 was constructed (benefits were not actually realized until after 1927). With these benefits and cost streams, Griliches calculated Benefit/ Cost ratios and an internal rate of return to investment.

This study utilized similar experiment station and field trial data along with country study data to obtain estimates of Modern Variety/Traditional Variety (MV/ TV) advantages (similar to the K term in Griliches' work). From these data and MV adoption rate data, benefits streams for crops and regions were constructed. Cost data series (from JUDD, BOYCE and EVENSON; PARDEY *et al.*, [1990]) were con-

TABLE 7

Rate of Return Estimates Summary*

	Number Reported	Percentage Distribution of IRRs					Approximate Median	IARC Studies**	
		0-20	21-40	41-60	61-100	100+		NARS	IARCs
Crop Research	207	.19	.19	.14	.26	.21	58		
Livestock Research	52	.21	.31	.25	.12	.09	36		
Aggregate Research	126	.16	.27	.29	.19	.09	45		
Private Sector Spill-In	11	.18	.09	.45	.27	0	48		
Ex Ante Studies	87	.32	.34	.21	.07	.06	42		
Agricultural Extension	81	.26	.23	.16	.21	.13	41		
By Methods									
Project Evaluation	121	.25	.31	.14	.24	.07	40		
Statistical	254	.14	.20	.23	.22	.20	50		
By Region									
OECD	146	.15	.35	.21	.17	.11	40		
Asia	120	.08	.18	.21	.26	.26	67	83	115
Latin America	80	.15	.29	.29	.22	.06	47	31	39
Africa	44	.27	.18	.18	.22	.05	37	9	68

*Note : * From* E*VENSON* *[2001].*

*** Estimates from* E*VENSON* *[2003].*

structed. From these series Internal Rate of Return estimates were computed. These are reported in Table 7, where a summary of other IRRs (EVENSON [2001]) is also reported. The IRRs calculated from these estimates are similar to those reported in other studies except for NARS in Africa where they are lower because of long periods of NARS ineffectiveness[7].

4 Conclusions

The Green Revolution produced technological innovations enabling tremendous welfare gains to consumers in virtually every country in the world. The aggregate supply increase from the Green Revolution produced significant declines in the costs of food in all countries (including the developed countries). Green Revolution gains were realized unevenly across regions and countries. Farm incomes were affected unevenly. Farmers with access to MVs gained income. Farmers without access to MVs generally lost income as prices declined.

We provided a test of the Evenson-Kislev Research as Search model utilizing data from national and international plant breeding programs in developing countries. Data for five crops — wheat, rice, maize, beans and potatoes — were analyzed. These were the dominant Green Revolution crops.

This paper also evaluated the net impact of the building of the international research centers on investment in the national programs. This effect has two parts. The recharge effect is positive. The competition or substitution effect is negative. That is, internationally crossed modern varieties compete with modern varieties crossed in the national programs.

This analysis showed that there are implicit scale economies affecting national investment in agricultural research. The analysis also showed that rural population densities stimulate investment in research. The international germplasm effect on investment in the national programs was related to both size of program (hectares planted) and population density. For small programs and for countries with low population densities, competition effects of international germplasm dominated. For larger countries and population dense countries, recharge effects dominated. For all developing countries (weighted by population density and hectares planted), the net impact of international germplasm was positive. The doubling of the investment in the international centers from 1965 to 1985 stimulated 18 percent more investment in national programs.

In Part II, we computed internal rates of return (IRRs) in the spirit of the original Griliches work on hybrid corn. The original IRR for hybrid corn, computed by Griliches was 43 percent. Studies reviewed by EVENSON [2001] reported similar IRRs with variations by region. Our calculations in this paper show that IARC investments yield very high IRRs, while NARS investments were somewhat lower. NARS IRRs for Africa were quite low when full costs were considered.

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[7] The internal rate of return (IRR) is the rate at which the net present value of benefits equals the net present values of all costs (see EVENSON [2001] for details).

The Green Revolution had profound effects on human welfare (child mortality, morbidity, malnutrition). We do not document these effects here. But in the tradition of Griliches, we believe that we have shown, as he did, that crop genetic improvement programs have a high payoff. ■

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