Evaluating Agricultural Research and Productivity

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MEASURING THE REQUIREMENTS AND BENEFITS OF PRODUCTIVITY MAINTENANCE RESEARCH

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"Now here, you see, it takes all the running you can do to keep in the same place."

The Red Queen, in Lewis Carroll's
Through the Looking Glass.

INTRODUCTION

Lewis Carroll's Red Queen aptly describes the activities of researchers who work in support of maintaining productivity in modern agriculture. It is broadly perceived that after traditional production practices and cultivars are replaced by those producing higher output, a certain amount of research will be needed to sustain the gains that have been made. It also is argued that the higher agricultural resource productivity becomes, the greater will be the activities needed to maintain the existing productivity level.

Recognition and quantification of the relationships involved has become important for several reasons. Perhaps one of the most important is related to mechanisms for funding agriculture research. While private sector research in support of maintaining agricultural productivity is becoming even more significant, an important component of the total effort remains in the public sector. In the minds of many in the agricultural establishment, there are good reasons for continuing to support public work, but I will not go into them here. However, maintaining this support from legislative bodies dominated by non-farm interests is becoming increasingly difficult, particularly under the present conditions facing U.S. agriculture. One reason is the presumption by some that reduced support for agricultural research and extension will, at worst, merely slow agricultural productivity growth. Some see this as not at all a bad result. Current over-supply conditions in agriculture are creating a major drain on the public treasury, and further increases in productivity are seen as a stimulus to even worse problems.

Those in agriculture generally reject these arguments. The "Red Queen" argument suggests that significant reductions in research support and related extension activities would not merely halt productivity growth. Actual declines may occur. Further, the association of high productivity with oversupply problems misses the point rather badly. Price and supply management policies we have followed, together with a number of macro economic developments affecting international markets, have been the principal causes of our current dilemma.

The remedies that are being sought via the 1985 Farm Bill depend almost entirely for their success on regaining more favorable export performance. Realistically, it is not reasonable to think of the export performance of the early 1980's as a target, but some improvement can be achieved under the right conditions. While effective export marketing depends on many complex factors, there is no more fundamental imperative to an export-oriented industry than that production costs be kept lower than production costs of competing producers abroad. This is true under any circumstances, but never more so than when severe competition is being faced on international markets. Continued research in support of productivity gains here is what makes low-cost production possible. However, the U.S. has no monopoly on the option of improving productivity and lowering production costs of agricultural products through research. High payoffs to public-sector research in support of agricultural productivity are as well documented for foreign countries as they are here. Without question, the present competition we face is partly because others have cashed in on these payoffs. The U.S. can hardly afford a back off in its commitment to maintain low-cost production opportunities here under these circumstances.

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Though the case for maintaining the even increasing agricultural resource productivity seems quite clear, the definition of maintenance research seems to be less so. I will proceed with an examination of what maintenance research is perceived to be, and how it is to be differentiated from non-maintenance research. Some evidence on the scope and nature of maintenance research activities will then be considered. Next, I will present some results from attempts to estimate structures formulated specifically to quantify the processes involved. The paper then concludes with some observations about possibilities for future work.

MAINTENANCE RESEARCH--THE BROAD DEFINITION

To many, the concept of maintenance research encompasses a very broad set of activities designed to counter a very broad set of forces that can reduce productivity, or profitability, in commercial agriculture. Somewhat surprisingly, eight different individuals who knew I was preparing this paper have independently recommended Plucknett and Smith's 1986 Bioscience article to me. Their very informative piece adopts what I consider to be a typically broad definition of maintenance research. A reasonable summary statement might be that maintenance research is any research required to maintain resource productivity, or profitability, as a result of changes in the environment surrounding production. For purposes of discussion, three dimensions of environmental change may be distinguished: physical change, economic change, and biological change.

Examples of physical change in the environment causing a need for maintenance research include soil erosion, salt accumulation under sustained irrigated agriculture, and increasing levels of air pollutants. As problems of these kinds emerge, resource productivity under existing production systems may decline unless further research programs are undertaken to develop ways of preventing or correcting emerging problems. Such research activities may represent very high payoff options even though they produce no secular improvement in resource productivity.

Sustained changes in prices of either inputs or farm products also can have the effect of making existing production practices, cropping systems, and cultivars look unattractive to profit-seeking producers. When these occur, research efforts may be needed to develop new production practices, or even entirely new crop and livestock enterprise combinations, for affected areas. Fundamentally, the arguments here rest on the same foundation as induced innovation theory. ". . . technical change is guided along an efficient path by price signals in the market" (Hayami and Ruttan, p. 57). An emerging set of prices can draw forth technology development favoring processes for using low-priced resources and saving expensive ones. But if prices then go on a new path so that even allocatively efficient use of resources with known technology becomes unprofitable, further development of yet newer technology may be called for to restore profitability of production.

Though somewhat of a side issue relative to today's discussion, the themes raised during consideration of the 1985 Farm Bill could have important implications in the future. The rhetoric emphasized a desire to legislate "market-oriented" farm programs. In the Administration's proposed bill, this meant drastically lower loan rates and target prices. The Administration had three objectives: 1) to make our program commodities price competitive, especially in international trade, and to remove the government's role as a buyer; 2) to reduce the role of government payments in farm income; and 3) to eliminate government controls on decision-making on the farm. The legislation enacted did drop loan rates, but target prices were changed little. The first objective was addressed, but the second two were not. It is unclear whether we will move to complete this agenda, or how rapidly if we do. However, in today's political environment, changes in this direction are a distinct possibility regardless of whether they occur in an abrupt fashion as suggested by the Administration, or with provisions for adjustment as, for example, in the Boschwitz-Boren proposed legislation. Resulting economic signals for farmers could well motivate demands for production technologies quite different from those presently in use. Continued, or even accelerated devaluation of land could result and grain production with lower yields per acre and a quite different input mix could be favored. It seems likely that the research establishment would need to undertake major new initiatives in response to such conditions.

The final dimension of environmental change that may trigger needs for maintenance research is biological change. Agricultural production processes are biological in character, and the focus of agricultural research is on improving productivity in biological production systems. Many research activities are directed toward developing direct suppressants of plant and animal pests via pesticides, herbicides, cultural practices, etc. Others emphasize breeding and selecting for crop and animal traits that provide resistance to the pests that are most prevalent and damaging under current field conditions. However, the composition of pest populations is neither constant nor unresponsive to the environment. Farmer adoption of direct suppressants of current pests, and adoption of crop and animals having resistance to existing dominant classes of pests alters the environment in which these pests live. Natural selection then comes into play. Those pests which were formerly prevalent recede in numbers. Successor generations will be dominated by those which can survive, or even thrive, in the new environment created by prior introduction of practices designed to control the earlier generation. The result is that the initial positive productivity effects from introducing such practices, inputs, and genetic strains, can decay over time. This produces requirements for maintenance research to compensate for the loss of productivity resulting from this biological process.

If one adopts the broad definition of maintenance research, then how are we to define non-maintenance research? It would appear that it is any research designed to improve productivity above the best previously attained level, regardless of whether the environment is changed or unchanged. While the distinction between the two is meaningful for certain purposes, it should not be over-emphasized. Plucknett and Smith have noted that "maintenance is an integral part of agricultural research, not a separate category. Upholding yield gains is the core concept of maintenance research, and it applies to all improved crops in both industrial nations and developing countries" (p. 40). The nature of the work undertaken by scientists in pursuing maintenance research is fundamentally no different from that done in non-maintenance research. Benefits from the two are also measured in identical ways. In each case it involves a comparison of results achievable from applying an extra increment of research inputs with results expected when that increment is not applied.

MAINTENANCE RESEARCH--THE NARROW DEFINITION

The narrow definition of maintenance research tends to focus on research activities designed to compensate for biological change in the environment. The origins of this form of maintenance research are not unique to agriculture, but the process whereby these needs arise is certainly more important in agriculture than in most other industries. This is because of the biological character of agricultural production processes mentioned earlier. Here, the <u>adoption</u> of many forms of productivity-increasing technology, by itself, induces biological change in the environment where production occurs. This change carries with it the seeds of subsequent decay or decline in the initial productivity gains achieved by adoption via the mechanisms described earlier. Decay is autonomous to the process.

Undoubtedly, certain forms of agricultural production technology are not subject to decay in this sense. However, it appears to be broadly applicable to many forms of agricultural technology regardless of whether it was developed to counter changes in the physical or economic dimensions of the environment, or whether it was introduced to improve productivity above the best previously attained level. The narrow definition of maintenance research associates it with research activities needed to maintain research productivity in the presence of an unchanged physical and economic environment. Within a given physical and economic environment, production techniques also may be replaced by new ones because the replacements produce better results than the best previously attained with the existing technology. Here, old production practices have become technologically obsolete. Other forms of obsolescence can be said to apply when changes in the economic or physical environment motivate development and adoption of replacement technologies.

In economics, productivity is generally taken to be a characteristic of a physical production process; i.e., a particular process for using well-defined inputs to produce one or more well-defined outputs. Productivity-oriented research is designed to increase the amount of output that can be realized from given input endowments. By extension, an economic definition of maintenance research would be research designed to maintain physical input/output ratios. Productivity obviously affects profitability, but it is not synonymous with profitability. The narrow definition excludes from maintenance research the development of new technologies designed to maintain profitability in the face of changing prices, and research to adapt to changing resource endowments.

A further comment is motivated by reflections on economists' use of the term "productivity." Discussion and illustrations of productivity change are often conducted in terms of crop yields per acre. The earlier quote from Plucknett and Smith is an example. While it may be true that, "upholding yield grains is the core concept of maintenance research," it is worth remembering that production per unit of land is merely the average physical product of the single resource (land). No economist working with a multiple input production process will want to assign overriding significance to the average physical product of a single resource as a measure of productivity for the overall process. Nor will he or she accept a comparison of average physical products of a resource in producing the same output under two processes as a basis for comparing productivity of those processes. Yields per acre, per milk cow, per hour, etc., are often useful productivity indicators, but full analysis requires more detailed consideration of input/output relationships.

Whether one works with a broad or narrow definition of maintenance research, the earlier judgement that it is an inseparable part of an overall agricultural research program still applies. Certainly, any attempt to introduce separate budgeting in support of maintenance research activities would introduce artificial distinctions that have no counterpart in the work actually done by research scientists.

Most of the discussion of work that follows will be based on the narrow definition of maintenance research. This is not to deny the importance of productivity-oriented research and extension motivated by changes in physical or economic conditions. Primarily, it is just to give a more specific focus to the paper, and to recognize the particular importance of biological adaptation as a factor causing a need for continued research to maintain productivity in agriculture.

EVIDENCE OF THE SCOPE AND NATURE OF MAINTENANCE RESEARCH ACTIVITIES

Evidence of biological adaptation among pests and pathogens is widely known. May indicates that hundreds of agricultural pest species are known to have acquired resistance to pesticides designed to control them. Plant breeding activities for many crops, particularly for small grains, concentrates heavily on improved resistance to diseases. Rapid rates of turnover in varieties grown commercially are cited as evidence of maintenance research activity. Ehrlich and Ehrlich indicate that the average life of a wheat variety in the northwestern U.S. is about 5 years. Hawaiian sugarcane varieties last about 10-12 years according to Evenson and Kislev. Others cite similar life spans for corn, cotton, soybeans, oats, and sorghum in the U.S.

Of course, evidence of varietal turnover need not, by itself, be indicative of maintenance research activity. To some degree, new varieties may be adapted because they have higher genetic potential for yields than the best achievable within existing varieties, and not because yields of existing varieties have fallen off. However, conventional wisdom on this matter is that much of the replacement occurs because yields of varieties in use begin to fall or because they are threatened.

Efforts to document specific instances of productivity declines due to biological adaptation have seldom been reported. Swallow, Norton, Brumback, and Buss reported results of two such efforts. Thirty-year trends of yields for three soybean varieties were examined to see if yield deterioration could be measured after controlling for weather and cultural practices. Yield declines were found in each case, but none were statistically significant. A further investigation was conducted to see if yield gains achieved in the Virginia soybean breeding program showed evidence of being less than those theoretically achievable in the absence of biological adaptation. Again, their empirical work did detect such a discrepancy, but statistical results were not conclusive.

Further research to identify and measure specific cases of productivity decline for individual crop and livestock enterprises under controlled conditions would be highly desirable for several reasons. One reason is that they help to provide specific content to descriptions of the biological decay process. However, evidence of this kind is not easily used in estimating aggregate maintenance research needs or payoffs from such research. Instances of biological decay are often episodic, and it is arguable that the frequency of their occurrence can only be described in terms of probabilities. Other work has been done to estimate research-productivity relationships for larger aggregates, and these often have incorporated the decay process, at least implicitly.

It is widely recognized that impacts of most research and extension expenditures on productivity occur with a distributed lag. Research activities require time for completion. Those that produce economically useful results are subject to adoption lags before they reach their maximum use level among producers. Adoption rates may be influenced by extension activities. Finally, impacts on productivity may decline as a result of obsolescence, or as a result of deterioration of the productivity-enhancing effects of new innovations.

In work relating production or productivity to research and extension expenditures, it has been common to estimate parameters of a single lag structure incorporating all of the above causes of lagged response to research and extension expenditure. Published work varies considerably in the degree to which they acknowledge that it is the stock of knowledge held by producers which can be presumed to affect output or productivity, whereas the flow of research and extension expenditure affects productivity through its effect on that stock. A very common finding is that the amount of research and/or extension expenditure in a certain year has impacts on output or productivity which initially rise with the passing of time, possibly remain constant for a time, and then fall to zero. The representation of decay or depreciation effects are, of course incorporated in the parameters of the lag structure. But under this approach, those effects are combined with knowledge generation effects, delivery service generation effects, and adoption rate effects, so that no separate estimates of the parameters of the decay or depreciation process emerge (see for example, Evenson, 1967; Havlicek and White; Lu, Cline and Quance; and White and Havlicek, among many others). Estimates of the lag at which research and/or extension effects on productivity begin to fall do indicate the lag at which negative decay or depreciation effects begin to dominate the other positive effects of research and extension expenditure. It also is possible to use results of these modeling efforts to estimate research and extension expenditures needed to sustain productivity at the observed level of any year while holding all other determinants constant at the level observed in that year. Such expenditures are legitimate estimates of maintenance research and expenditure outlays needed to maintain productivity or output at the level observed. A comparison of the estimated maintenance outlay with actual outlay for the year provides an estimate of the fraction of actual outlay devoted to maintenance.

ESTIMATING RESEARCH AND EXTENSION EFFECTS WITH AN EXPLICIT DECAY PROCESS

This section will present results of a modeling effort relating aggregate U.S. agricultural productivity to aggregate public expenditure on productivity-related research and extension activities. Decay or depreciation of research and extension effects are included explicitly.

Knowledge Creation

The modeling of knowledge creation is based on a conceptualization presented by Evenson in 1967. Let Q_t be defined as "the set of quality improvements of year t that result from research effort in year t, t-1, t-2, etc." (Evenson, p. 1419). More specifically, Q_t measures change in the stock of knowledge existing in year t. The stock of existing knowledge, K_t^*, is to be distinguished from the stock of effective productivity-sustaining knowledge that is actually in use in period t, K_t. Changes in the stock of existing knowledge are created through a "research production function" which contains research inputs R_t, R_{t-1}, R_{t-2}, etc. (measured in expenditure units) and random errors u_t, u_{t-1}, u_{t-2}, etc. By definition, the stock of existing knowledge changes by Q_t each time period. These results are reflected in equations (1) and (2). Here W(L) and C(L)

(1) $Q_t = W(L)R_t + C(L)u_t$

(2) $K^*_t - K^*_{t-1} = Q_t$

are polynomials in the lag operator L, and $L^s X_t = X_{t-s}$; s=0, 1, 2, . . .

An "extension production function" is introduced in which information transfer services, I_t, are related to current and lagged extension expenditures, E_t, E_{t-1}, E_{t-2}, . . ., and random errors v_t, v_{t-1}, v_{v-2}, . . .; equation (3). H(L) and D(L) are additional polynomials in the lag operator.

(3) $I_t = H(L)E_t + D(L)v_t$

Effective knowledge actually used at one time, K_t, is determined by the stock of knowledge used previously, by biological decay or depreciation of the previously used knowledge stock, by new knowledge that is brought into use, and by extension activity. However, adoption lags are involved in bringing recently generated knowledge into actual use. These considerations are captured in equation (4). A(L) is an additional polynomial in the lag

(4) $K_t = (\varphi)K_{t-1} + A(L)(K^*_t - K^*_{t-1}) + rI_t$

operator. It reflects adoption lags. To the extent that the adoption process can be described by a conventional "learning curve" the weights given to lag operators L^0, L^1, L^2, L^3, etc., are expected to be small for low order lags, rise to a peak for intermediate lags, and then fall to zero for high order lags. However, there appears to be no real reason to expect symmetry in this distributed lag function.

For an adoption process where all newly created knowledge is adopted, and where no obsolescence occurs, the coefficients of lag operators L^0, L^1, L^2, . . . in A(L) would sum to 1.0. But as noted earlier, obsolescence affects research and extension impacts on productivity. Many newly adopted practices and inputs substitute for presently used ones because they produce better results under the same conditions. Thus it is useful to think of A(L) as reflecting adoption of new knowledge above that which is replaced in use via obsolescence. With obsolescence, future knowledge in use, K_{t+s}, never reflects the full change in existing knowledge, K^*_t. This would be associated with a set of coefficients on L^0, L^1, L^2, ..., which sum to less than 1.0. Other factors may also account for a coefficient total less than unity. Some newly existing knowledge in K^*_t may offer technically feasible production possibilities that are unprofitable. Other knowledge may become technically or economically outmoded before it is adopted because of even newer additions to existing knowledge.

The φ parameter in equation (4) reflects biological decay. While obsolescence affects the transformation of research expenditures into effect knowledge via replacement of knowledge in use, decay occurs even in the absence of replacement. Thus, φ measures the proportion by which the productivity-sustaining capacity of K_{t-1} is reduced in time t as a result of biological adaptation.

Substituting (1) into (2), and then (2) and (3) into (4) yields equation (5). Since we may assume that $0 < \varphi < 1$, successive substitutions

(5) $K_t = (\varphi)\, K_{t-1} + A(L)\{W(L)R_t + C(L)u_t\} + r\{H(L)E_t + D(L)v_t\}$

may be made to derive equivalent forms, equations (6) and (7). As opposed

$$(6)\quad K_t = \sum_{s=0}^{\infty} (\varphi)^s A(L)\{W(L)R_{t-s} + C(L)u_{t-s}\} + \sum_{s=0}^{\infty} (\varphi)^s\{r[H(L)E_{t-s} + D(L)v_{t-s}]\}$$

$$(7)\quad K_t = F(L)\{A(L)W(L)R_t + rH(L)E_t\} + F(L)\{A(L)C(L)u_t + rD(L)v_t\}$$

to the other distributed lag functions which are not explicit, F(L) is an explicit distributed lag function, i.e.,

$$F(L) = \sum_{s=0}^{\infty} (\varphi)^s L^s.$$

It was noted earlier that most research has estimated parameters of a single lag structure on research and/or extension expenditure in productivity modeling. Often research and extension expenditures are aggregated in some fashion because of difficulties in estimating parameters of separate lag functions for each. Referring to equation (7), this imposes restrictions linking the lag function applicable to research expenditures, F(L)A(L)W(L), and that for extension expenditures, F(L)H(L), in addition to the restriction which follows from the common factor F(L). In extreme cases, they are assumed to be identical. Because of difficulties in estimating separate effects of several serially correlated aggregates of current and lagged R and E expenditures, it is usual to impose restrictions on the set of their coefficients. Examples include requiring that they follow an "inverted V" pattern (Evenson, 1967), or that they lie on a second degree Almon polynomial with zero end-point restrictions (Lu, Cline, and Quance; Havlicek and White; White and Havlicek). With this approach, estimates are then made of the parameters of a single, overall, lag function through which output or productivity is affected by aggregates of lagged R and E expenditures. In such cases coefficients of the decay process (φ in this case) cannot be determined.

The Model

The basic productivity model appears in equation (8).

$$(8)\quad Y_t = a + b_1X_{t1} + b_2X_{t2} + cK_t + e_t$$

All variables except X_{t2} are measured in logarithms.[1] Y_t is USDA's index of aggregate resource productivity in U.S. agriculture for year t. X_{t1} is percent of the U.S. population 25 years old or more who had completed high school in year t.[2] X_{t2} is a weather index for year t. Index values estimated by Stallings and Kost were updated by regressing the U.S. crop yield index on time, calculating the ratio of actual to predicted yield for each year, and splicing this series to the Stallings-Kost index series. K_t is the stock of effective knowledge actually used in year t. The residual, e_t, is a random error such that $e_t = \rho e_{t-1} + \epsilon_t$, and the ϵ_t are assumed to be independent normally distributed random variables with mean = 0 and variance = σ^2.

The model posits that the stock of effective knowledge used in year t is determined as in equation (9). Equation (9) is based directly on equation (7). However, it is in logarithmic form. R_t and E_t are aggregate production-oriented public expenditures on research and extension, respectively, each divided by the implicit deflator for government goods and services purchases. Errors in the knowledge and extension service generating processes are ignored except that allowance is made for first-order autocorrelation in residuals to the productivity equation. The single parameter in the lag function F(L) is estimated explicitly so that a unique estimate of the depreciation effect emerges. The product of the knowledge generation and adoption lag functions applicable to research expenditures, A(L)W(L), is represented as a single lag function. A separate, simple "lag function" for extension expenditures, $H(L) = \alpha L^0$, is employed on the assumption that there is no lag between commitment of resources to extension and generation of information-delivery services.

$$(9) \quad K_t = \sum_{s=0}^{\infty} \varphi^s \{\alpha E_{t-s} + \sum_{p=0}^{M} \beta_p R_{t-s-p}\}$$

Substituting (9) into (8) and writing γ and π_p for $c\alpha$ and $c\beta_p$, respectively, yields equation (10).

$$(10) \quad Y_t = a + b_1 X_{t1} + b_2 X_{t2} + \gamma \sum_{s=0}^{\infty} \varphi^s E_{t-s} + \sum_{p=0}^{M} \pi_p \sum_{s=0}^{\infty} \varphi^s R_{t-s-p} + e_t$$

The parameters to be estimated are a, b_1, b_2, ρ, φ, $\gamma = c\alpha$, and $\pi_p = c\beta_p$, p = 0, 1, . . . , M. Parameters c, α, and β_p are not identified, but the indicated functions of them are.

The coefficients π_p are further constrained to lie on an Almon polynomial having parameters λ_d, equation (11), and

$$(11) \quad \pi_p = \lambda_0 + \lambda_1 p + \cdots + \lambda_D p^D = \sum_{d=0}^{D} \lambda_d p^d \; ; \; p = 0, 1, \ldots, M$$

restrictions may be placed on the polynomial corresponding to requirements that either $\pi_0 = 0$, $\pi_M = 0$, or $\pi_0 = \pi_M = 0$. Thus, the parameters λ_d are estimated directly, and parameters π_p are estimated indirectly in terms of λ_d and p.

Principal interest centers on estimating the rate of decay in the productivity-sustaining capacity of knowledge generated through research and extension, and the overall impacts of research and extension expenditures on productivity. Here, φ estimates the elasticity of current effective knowledge with respect to effective knowledge existing one period earlier. The extent to which φ is less than 1.0 is a measure of depreciation of the productivity-sustaining capacity of knowledge used by producers. Elasticities of productivity with respect to current and previous extension expenditures are calculated as in equation (12). Elasticities with respect to research expenditures may be

$$(12) \quad \partial Y_t / \partial E_{t-s} = \gamma \varphi^s \; ; \; s = 0, 1, 2, \ldots$$

calculated recursively as in equation (13).

$$(13) \quad \partial Y_t / \partial R_{t-s} = \begin{cases} \pi_0 & ; \; s = 0 \\ \varphi \partial Y_t / \partial R_{t-(s-1)} + \pi_s & ; \; 1 \le s \le M \\ \varphi \partial Y_t / \partial R_{t-(s-1)} & ; \; s > M \end{cases}$$

Estimation

The appearance of summation indices running to infinity in equation (10) is the principal factor complicating estimation. The method for handling the problem is a variant on one suggested by Just (1974, 1977) and Estes, et al. Finite approximations to the infinite sums in equation (10) are used. Estimation proceeds by using an iterative non-linear least squares approach appropriate for a first-order autoregressive error structure. The sum of squares function is concentrated on the parameter φ. Search over the range $0 < \varphi < 1$ is then employed to find the φ value within a tolerance of .0001 that minimizes the sum of ϵ_t^2 values, together with associated estimates of other parameters.

Just (1977) has shown that though such estimates are not truly maximum likelihood estimators, they asymptotically approach maximum likelihood estimators for large sample size. This motivates use of the inverse of the information matrix for calculating estimates of asymptotic standard errors of coefficients.

As with most approaches using Almon polynomials, it is necessary to search over alternative D and M values and alternative end-point restrictions. An end-point restriction corresponding to $\pi_M = 0$ was imposed in most cases and the initial search focused primarily on a D value of 2 and a substantial range of M values. Results suggested that D = 1 produced polynomial "shapes" similar to those for D = 2, and results that were otherwise superior for all M values. The criterion for selecting final results was minimum standard error of estimate (SEE) among outcomes that were economically meaningful.

Results and Analysis

Table 1 presents parameter estimates and related statistics for the equation best representing the relationship between aggregate resource productivity in U.S. agriculture and education, weather, and aggregate public R and E expenditures. The π_p values have been constrained to lie on a first degree Almon polynomial with a maximum lag of 7 years, and it is constrained so that $\pi_7 = 0$.

Table 1. Productivity Model Results Using a Linear Almon Polynomial with 7-Year Maximum Lag and Restriction $\pi_7 = 0$.

Parameter	Parameter Estimates	Asymptotic Standard Error[a]
a	1.5346	.2957
b_1	.2600	.1003
b_2	.0030	.0007
γ	.0402	.0404
λ_0[b]	.0085	.0033
φ	.7734	.0857
ρ	.1563	.1686

$F(6, 33) = 310.8$
Durbin-Watson d = 1.83[c]
$R^2 = .983$
Standard Error of Estimate = .0252[c]

[a]From the inverse of the information matrix.
[b]The estimate of λ_1 (-.0012) may be determined from the restriction $\hat{\pi}_7 = \hat{\lambda}_0 + \hat{\lambda}_1 7 = 0$.
[c]Calculated using estimates of ϵ_t.

All coefficients have the expected signs, and except for $\hat{\gamma}$ and $\hat{\rho}$, all are at least 2.5 times their standard errors. A one percent increase in the education index is estimated to produce a .26 percent increase in productivity, and a unit increase in the weather index is associated with a .3 percent increase in productivity. The estimated coefficient of the AR1 error process is only .16. This small value and associated standard error are evidence of only modest first order serial correlation in the e_t.

Research and extension effects on productivity are reflected in estimates of γ, λ_0, λ_1, and φ. The elasticity with respect to current extension expenditure is estimated to be .04, but its relatively high standard error suggests caution in accepting this value. The π_p coefficients are estimated as $\hat{\lambda}_0 + \hat{\lambda}_1 p$; $p = 0, 1, \ldots, 7$; and $\hat{\lambda}_0$ appears to be estimated with reasonable precision. The coefficient λ_1 is estimated from the restriction $\hat{\lambda}_1 = -\hat{\lambda}_0/7$, so that subject to this restriction, the ratio of this estimate to its standard error is the same as for $\hat{\lambda}_0$. Accordingly, the set of $\hat{\pi}_p$ estimates form a linearly declining sequence starting at .0085 for $p = 0$ and falling to 0 for $p = 7$. This suggests that public research expenditures have their greatest impact on undepreciated new knowledge used by farmers in the year when the expenditure is made, and that the lagged effects decline monotonically to zero after 7 years. Alternatively, this implies that for a typical mix of research expenditures in any year, the greatest share goes for activities having immediate impacts, or for activities that "pay off" in a short time, and lesser shares go for activities that will first be used by farmers after a longer delay. Most conventional descriptions of knowledge generation and adoption processes related to agriculture suggest a set of π_p coefficients that would first increase with p, and then decline to zero for larger p. The conventional expectation would also call for non-zero π_p values at lags substantially higher than 7.

The estimate of φ suggests that a one percent increase in the stock of effective knowledge used by farmers in one year, ceteris paribus, will result in only a .77 percent increase in the following year's stock. The complement, .23 percent, represents depreciation in the effective stock (its productivity-sustaining capacity) due to biological adaptation. Further, this decay process is a continuing one so that the elasticity of effective knowledge used in year t with respect to effective knowledge used in year t-s is estimated to be $.77^s$.

Productivity, as modeled here, depends on the current stock of knowledge, which, in turn, is defined in terms of present and all past research and extension expenditures. Using equations 12 and 13, together with parameter estimates in Table 1, elasticities with respect to R and E expenditures lagged any number of time periods can be estimated. Such estimates for lags of 1 through 15 years are shown graphically in Figure 1. Each set of elasticities is displayed as a continuous curve to facilitate presentation, but the actual elasticities are only defined for integer-valued lags. As Figure 1 shows, both elasticities approach 0 as the lag goes to infinity, but the research elasticities increase up to a lag of about 3 years before starting an asymptotic decline, while the extension impacts decline from the outset. Initial elasticities with respect to extension expenditures are much higher than those for research, but for lags of 4 or more, the rankings are reversed.

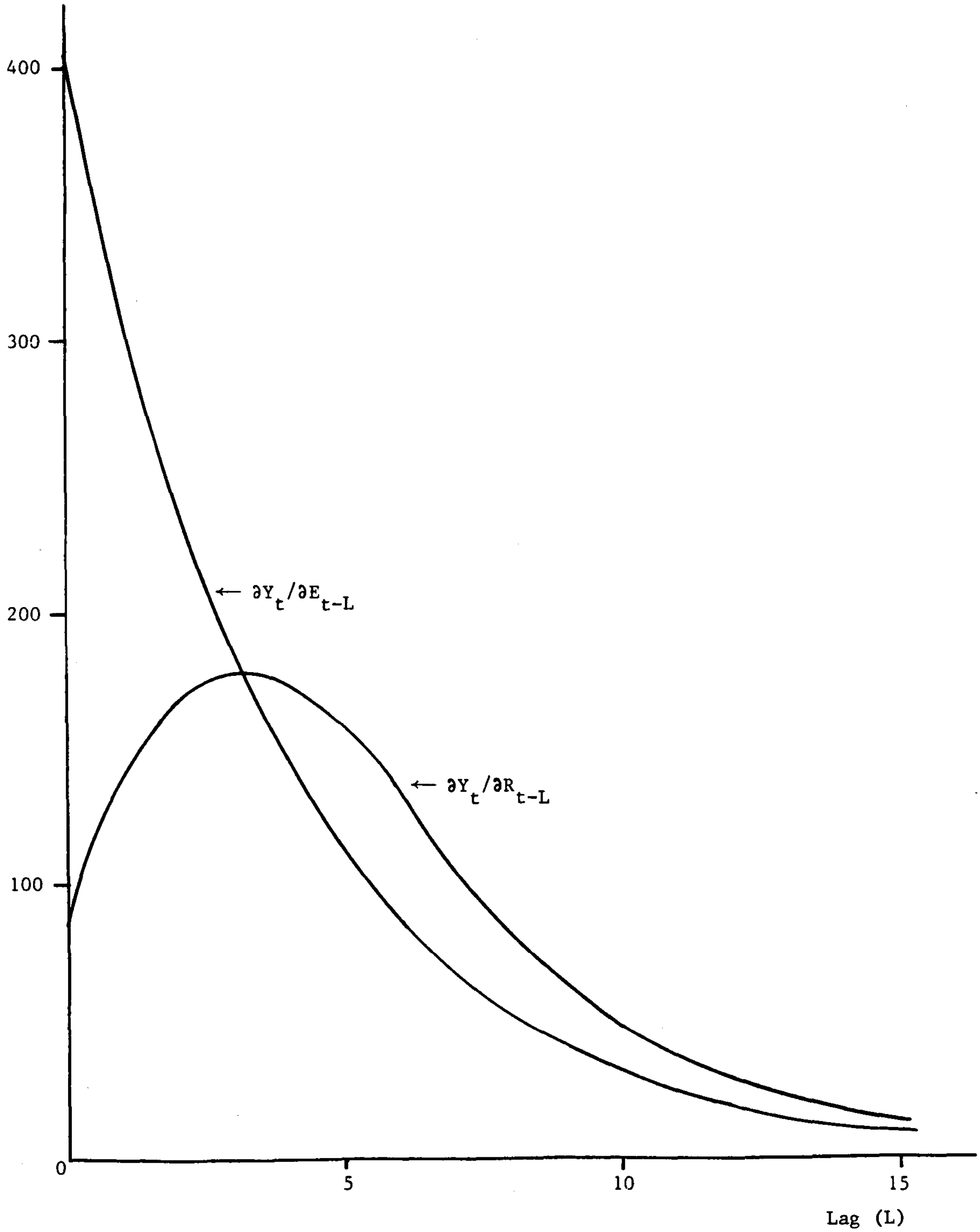
These results may also be used to estimate

$$\sum_{s=0}^{\infty} \partial Y_t/\partial R_{t-s} = .1501 \text{ and}$$

$$\sum_{s=0}^{\infty} \partial Y_t/\partial E_{t-s} = .1775,$$

so that the estimated long-run elasticity with respect to extension expenditures is found to be about 18 percent higher than that for research expenditures. Mean 1942-81 productivity, research expenditures, and extension expenditures were used to convert these long-run elasticities to long-run marginal effects of R and E expenditures on productivity. The

Figure 1. Research and Extension Expenditure Effects on Productivity (x10^4).



results suggest that at the margin, an additional dollar allocated to extension activities had an impact on productivity 4.57 times as large as the effect of an additional dollar spent on research.

The seemingly large effects of extension expenditures relative to research expenditure effects are, of course, subject to considerable uncertainty. The estimate of γ establishes the "height" of the $\partial Y_t / \partial E_{t-s}$ curve in Figure 1, and judging from standard errors, it is estimated with substantially less reliability than any other essential coefficient in the model. Indeed, at the outset of the study, reviews of prior research led us to expect no success in estimating separate research and extension effects because of correlation among education, research expenditures, and extension expenditures. It was only after finding promising results with structures that combined these effects that the present formulation was examined.

Results from this model were subjected to one further statistical test. The hypothesis that neither research nor extension expenditures affect productivity was examined by testing the hypothesis $\gamma = \lambda_0 = \varphi = 0$ using an asymptotic likelihood ratio test.[3] Under the null hypothesis, the test statistic is asymptotically distributed as Chi-square with 3 degrees of freedom. The calculated value, 14.9, leads to rejection of the null hypothesis at the .005 level of significance. This provides very strong evidence against the possibility that all these parameters are equal to zero.

Results Under Alternative Specifications

As noted earlier, the above results were selected after examining estimation outcomes under a variety of specifications of degree (D), maximum lag (M), and end point restrictions on the Almon polynomial. Some lack of robustness was expected and observed because of correlation among the data on explanatory variables. However, an unexpected form of non-robustness also emerged. For given D, M, and end-point restrictions, the estimation technique employs a systematic search of the sum of squares function for $\hat{\varphi}$ values in the range of $.0001 \leq \hat{\varphi} \leq .9999$. The logic against $\hat{\varphi}$ values very close to 0 (immediate total decay) or 1 (no decay) seemed sufficiently strong that we expected the minimum sum of squares to always be associated with a $\hat{\varphi}$ value "comfortably" away from either end point. This frequently was not the case, though the reasons are not clear. When this occurred, however, the overall fit was always inferior to results with other D, M and end point restrictions where an interior optimal $\hat{\varphi}$ value was found.

The principal points that emerge from examining alternative specifications are:

1. Polynomials having an "inverted V" shape are found only when the constraint $\pi_0 = 0$ is imposed, and associated SEEs are higher than without this constraint. Even with third degree polynomials that were examined but not reported, the statistical evidence favors polynomials that initially fall with positive lags.

2. Estimates of b_1 and γ are unstable, though those associated with the equation judged to be best are centrally located within the set of estimates obtained with other specifications.

3. Long-run estimated research impacts are more robust across alternative specifications than are extension impacts. Finally, a related study of the relationship between wheat yields and wheat production oriented research expenditures in Washington was conducted using a similar model formulation (Heim and Blakeslee). Here also, the best representation of the relationship involved a declining first degree Almon polynomial with a 7-year maximum lag.

Maintenance Research and Extension Expenditures

Decay of the ability of knowledge to sustain agricultural productivity due to biological adaptation implies that some level of continuing expenditure is necessary if a productivity decline is to be avoided. The productivity model estimated here was used to estimate the fraction of actual R and E expenditure that was required for productivity maintenance in each of the 40 years from 1942 to 1981. Two sets of measures were calculated. For the first set of measures, expenditures required to generate a current year expected productivity equal to last year's level were calculated for each year. Actual expenditure in years t-1, t-2, . . ., were used in this calculation. Results were expressed as a percent of actual current year R and E expenditure and they appear in Figure 2 as the broken line.

The historical time series on real research and extension expenditure trends upward. If one simply stopped the growth of expenditure at some time and held it constant thereafter, productivity would decline asymptotically to some lower level as the decay process affected knowledge generated by more recent expenditures. For the second set of maintenance expenditure measures, the model was used to determine the level of expenditure which, if continued indefinitely, would permit maintenance of expected productivity at the level observed in each year. This "steady state" expenditure level for each year was expressed as a percent of actual expenditure, and results are plotted as the solid line in Figure 2.

In the early 1940's, the start of the period under consideration, real research and extension expenditures were well below those of the late 1930's. Existing productivity levels were reflecting these substantially higher expenditures in the immediately preceding years since not enough time has elapsed for decay to diminish their effects significantly. This is reflected in Figure 2 by estimates showing that maintenance-level expenditures were actually higher than total expenditures. Maintenance expenditure as a percent of total declined thereafter as expenditures recovered and continued to increase. Though fluctuations occurred, no apparent trend in the maintenance expenditure percents is visible from the late 1940's through the late 1960's. However, from the mid-1970's onward, both sets of percentages seem to be on a higher plateau.

The percent of actual expenditure needed to maintain previous year's expected productivity is inherently more volatile than the steady-state expenditure needed to maintain current productivity. The former is more sensitive to the pattern of expenditure in the recent past than is the latter. However, both indicators suggest that very substantial portions of current expenditures are required to maintain productivity and lesser fractions are contributing to further increases in resource productivity. Since 1973, roughly 70-80 percent of each year's research and extension expenditure was needed just to maintain the prior year's expected productivity. However, real expenditures increased in all but one of these years. If expenditure growth had stopped in any of these years, expected productivity in subsequent years would have declined. Annual expenditures necessary to sustain each year's productivity indefinitely are higher. Figure 2 shows that since 1972 such expenditures have been about 90 percent of actual expenditures in each year.

Of course, expenditures along each line in Figure 2 generally relate to maintenance of productivity at increasingly higher levels as time progresses. Estimates of expected productivity given mean weather and actual educational attainment, and lagged research and extension expenditures increase monotonically in each year since 1944. This is due not only to generally rising real expenditure but also to monotonically increasing levels of general education.

SUMMARY AND OBSERVATIONS ON FUTURE WORK

Available evidence that focuses specifically on depreciation of research and extension effects for individual crops is fragmentary and inconclusive. Further work to document and quantity specific cases should add substantially to our understanding of the processes that are at work in generating maintenance research requirements.

The exploratory work reported here in which aggregate resource productivity in U.S. agriculture is related to public expenditures on research and extension and other variables suggests that productivity-sustaining effects of public expenditures decay quite rapidly. These results further suggest that about 90 percent of recent research and extension expenditures have been required to maintain productivity.

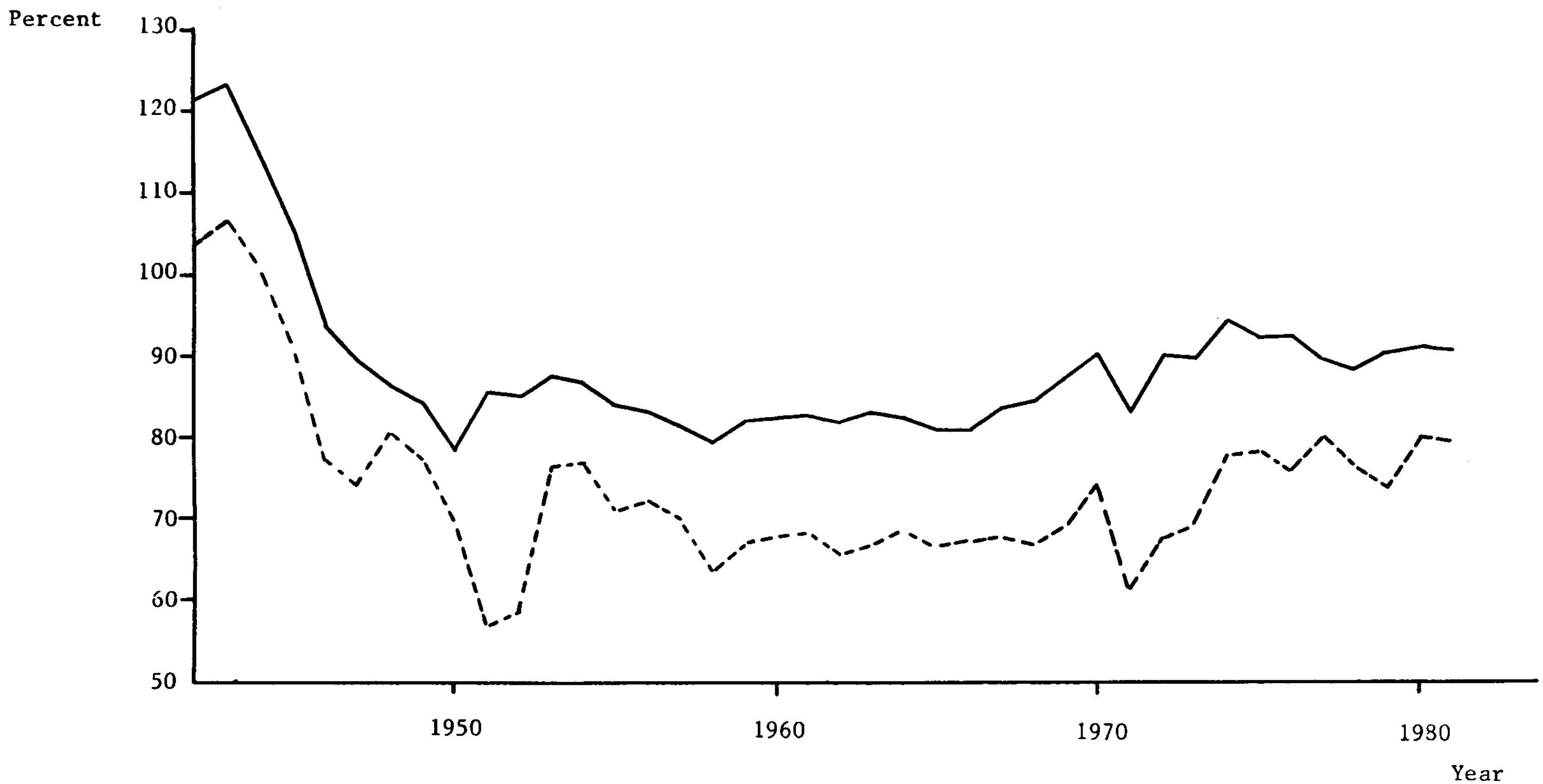


Figure 2. Percent of Actual R and E Expenditure Required to Achieve Last Year's Productivity (- - -), and to Sustain Each Year's Productivity Indefinitely (——).

An analog to Plucknett and Smith's observation that, "maintenance is an integral part of agricultural research," seems applicable to research on research productivity. That is to say, measuring depreciation of research effects, and hence maintenance research requirements, is an integral part of measuring overall agricultural research productivity. Unfortunately, the process whereby research and extension efforts are translated into productivity change is extremely complex.

Some of the complexities lie in the lag structures that are involved. To estimate depreciation rates, one must not only specify a particular depreciation process, but also separate lag structures reflecting other processes that give rise to lagged effects. For econometric applications, this requires use of considerable a priori knowledge, and it is not clear that our knowledge base is adequate for these requirements. Several examples appear in the work reported here. Depreciation effects are introduced by positing that productivity-sustaining capacity of existing knowledge declines geometrically. This may be a reasonable simplifying approximation, but it is by no means the only possibility. The best fitting weights for the process modeling combined knowledge creation and adoption were found to monotonically decline with increasing lag, and reach zero in only 7 years. Most previous work places restrictions on the weights that essentially force them to risk initially with increasing lag. Justifications typically cite long lags for knowledge creation and adoption as the reason. It is not clear that this reasoning takes proper account of the fact that some (perhaps many?) research dollars pay for "brush fire" work by research in which "off the shelf" knowledge is used to formulate remedies to newly experienced problems. In other cases, progressive farmers go directly to researchers for their results. In these instances, research dollars are paying for extension-like services having immediate payoffs that may be very high. Even for long-lived research efforts, the distribution of research expenditure over the life of the project can be skewed toward the "payoff end," and this too can affect the pattern of lagged expenditure coefficients. It also is conventional to reject negative coefficients on lagged expenditures as contradictory to a priori knowledge. Even in this case, I am not totally convinced. When "last adopters" are forced to take on new practices that they are not equipped to handle, either because of management ability or resource availability, it is not clear that the effects on aggregate productivity will be non-negative. Such issues need attention in future work.

More general problems related to functional forms for productivity models may also yield useful insights if pursued. In most empirical work, a variety of functional forms may give satisfactory results in many applications so long as little extrapolation is involved. Multiplicative Cobb-Douglass-like forms for a productivity model allow for important interactions without unduly complicating estimation. However, a model like that described earlier implies that if research or extension expenditure in any year is zero, then productivity will be zero for all years thereafter. Alternative specifications that allow for interaction, but do not force productivity to approach zero as research approaches zero, would be of interest. However, the econometric problems are likely to be formidable.

In my view, reliable quantification of the mechanisms through which maintenance research requirements arise remains to be accomplished, but the fragmentary evidence available suggests that payoffs from maintenance research are high. I believe that this subject deserves continued attention in the agenda of "research on research" as we seek continued understanding and support of efforts to maintain and improve productivity in agriculture here and abroad.

FOOTNOTES

1. With this formulation, a zero value of the educational attainment measure or for any current or lagged research or extension expenditure implies a zero current productivity index value. Clearly, this is not tenable. This formulation is used because it affords a relatively simple way to allow for falling marginal impacts of key variables and interaction between them. As with most applied work of this kind, results should be taken as reasonable appropriations only within the range of data actually observed and for modest extrapolations. Nevertheless, the limitations of the logarithmic form in this application may be more serious than in most.

2. This is not the educational attainment index used by White and Havlicek. Their's is an updated version of one constructed by Evenson, and also used by Cline and Lu, Cline and Quance. However, it is questionable whether information is available for a consistent updating. The original index was constructed so that, conceptually, its value in each year is a weighted average of factors reported by Welch which estimate relative earning capacities of workers in U.S. agriculture with different schooling in 1959. The weights applied to each of Welch's factors for any year are to measure the fraction of agricultural manpower that had the associated schooling level in that year. The implicit assumption that Welch's weights are constant and appropriate for agriculture in all years during 1939-81 is not appealing. Further, the index values for most of the first 20 years actually appear to be interpolations between the very few points where available data permitted direct calculations.

   Percent of the U.S. population completing high school is also only a proxy for the correct index, and many interpolations were again necessary for the early years. However, it is readily accessible and, on balance, may serve as well as the alternative. Empirically, both have similar properties. For the overlap years (1939-72), the simple correlation is .99. Both series contain strong trends, and the partial correlation between the 2, conditional on linear trend, is .36.

3. Note that since estimation was performed under a restriction on the Almon polynomial such that $\lambda_1 = -\lambda_0/7$, this is equivalent to the hypothesis $\gamma = \lambda_0 = \lambda_1 = \varphi = 0$.

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