The World's Largest Open Access Agricultural & Applied Economics Digital Library

This document is discoverable and free to researchers across the globe due to the work of AgEcon Search.

Help ensure our sustainability.

Give to AgEcon Search

AgEcon Search
http://ageconsearch.umn.edu
aesearch@umn.edu

*Papers downloaded from **AgEcon Search** may be used for non-commercial purposes and personal study only. No other use, including posting to another Internet site, is permitted without permission from the copyright owner (not AgEcon Search), or as allowed under the provisions of Fair Use, U.S. Copyright Act, Title 17 U.S.C.*

MANCHES

86/5

Manchester Working Papers in Agricultural Economics

The Production Function Approach to the Relationship Between Productivity Growth and R & D

Colin Thirtle

(WP/05)

GIANNINI FOUNDATION OF AGRICULTURAL ECONOMICS LIBRARY
WITHDRAWN
DEC 10 1986

ARDUUS AD SOLEM

Department of Agricultural Economics

Faculty of Economic and Social Studies
University of Manchester
Manchester U.K.

The Production Function Approach to the Relationship Between Productivity Growth and R & D

Colin Thirtle

(WP/05)

The Production Function Approach to the Relationship Between Productivity Growth and R and D

1) Introduction

Recent surveys[1] of the literature on the returns to public sector agricultural research investments show that several evaluation techniques have been used. Ex post cost-benefit analysis has proved popular at the individual project and crop level and the production function approach has been applied to the agricultural sector in aggregate, to its component parts (i.e., dairy, poultry, livestock, crops, etc.) and to individual crops. Less common are ex-ante evaluations using scoring systems, cost-benefit analysis, simulation and programming models.

This paper outlines the ex post, production function approach, discusses its suitability for evaluating national agricultural research in aggregate and explains how it may be applied to experimental results from a specific research programme on oilseed rape. The difficulties inherent in attempting to model the relationship between R and D expenditures and productivity are also discussed.

2) The Production Function Approach[2]

Early studies included expenditure on research (and extension) as an input in the Cobb Douglas production function. The dependent variable was aggregate agricultural output for the USA (Griliches 1964, Evenson 1967) and for India (Kahlon et al, 1977). Peterson (1967) considered poulty, while Bredahl and Peterson (1976) and Norton (1981) compared grains, dairy, poultry and livestock.[3]

Using a simple two input example, the model underlying these studies has been summarised by Griliches (1973) as follows. Let

(1) $Q = TF(A,L)$, where Q is output, A and L measure inputs of land and labour and T represents the current state of technology. Then let

(2) $T = G(K,O)$ and

(3) $K_t = \Sigma w_i R_{t-i}$, where K is a measure of the accumulated (and still productive) research capital (stock of knowledge) and O represents all other forces affecting total factor productivity. R_{t-i} measures the real gross investment in research at time t-i and the w_i's are weights connecting past research to the current state of knowledge, K_t.

Typically, for estimation purposes, the functions F and G are both specified as Cobb Douglas,[4] so that the model simplifies to

$$(4) \quad Q = Ce^{\lambda t} K^{\gamma} A^{\alpha} L^{1-\alpha}$$

where C is a constant, O is represented by the time trend, λt and γ may be interpreted as the output elasticity of research capital.

Alternatively, taking logarithms and rearranging[5] gives,

$$(5) \quad \ln P = \ln Q - \alpha \ln A - (1-\alpha) \ln L = \lambda t + \gamma \ln K,$$

where α and $(1-\alpha)$ are interpreted as factor shares,[6] so that P is a total factor productivity index which is explained by a time trend and the stock of research capital. Since the conventional inputs are incorporated in the total productivity index, changes in the index can be accounted for by non-conventional inputs which in addition to research capital may include education and, in the case of agricultural production, the weather. This type of function has been fitted to data for U.S. agriculture by Evenson (1967), Cline and Lu (1976), Lu, Quance and Liu (1978), Lu, Cline and Quance (1979), Knutson and Tweeten (1979) and White and Havlicek (1982); to Australian data by Hastings (1981) and to UK agriculture by Doyle and Ridout (1985).

3) Treatment of Research Expenditures

Models based on equations such as (5), above, explain changes in total factor productivity by changes in the stock of research capital. The difficulties involved in calculating total factor productivity indices[7] have generated a considerable literature (Thirtle, 1986). Early studies such as Griliches (1964) and Minasian (1969) defined the independent variable as

$$(6) \quad K_t = \sum_{i=1}^{n} R_{t-i},$$

with the value of n determined by data availability.[8]

Equation (6) is a poor formulation since the wi's in equation (3) were intended to reflect (1) the time lag between research expenditures and productivity change and (2) the depreciation of the knowledge stock due to obsolescence (Griliches 1980, p.344). In agriculture, depreciation of biochemical technology due to diseases, insect pests and parasites is important. Maintenance expenditures are required or the net technology stock will decline (Evenson, 1982). Most simply, equation (6) can be altered to allow for a fixed rate of depreciation (δ). Evenson (1967) defines

(7) $I_t = w(L)R_t$, where I_t is the improvement in technology in year t, and is related to past research expenditures by the lag operator w(L). Then,

(8) $K_t = I_t + (1-\delta)K_{t-1}$, incorporates both the lag structure and a fixed rate of depreciation, δ. Due to the complexity of the several lags involved (also discussed by Griliches 1979, p.101-2), Evenson abandons equation (8) in empirical work, using instead an inverted V-shaped distributed lag structure.

The later US studies mentioned above all follow Evenson, but replace the inverted V with a second degree polynomial lag structure in estimating equations very similar to this example from Lu, Cline and Quance (1979),

(9) $P_t = \prod_{i=0}^{n} R_{t-i}^{\alpha_i} O_t^{\delta} E_t^{\beta_t} e^{\gamma w_t u_t}$

where P_t is the productivity index, R_{t-1} are production orientated research expenditures, O_t are other research and <u>extension</u> expenditures, and E_t is an education index. The "error term" is divided between the effect of the weather, w_t, and other errors that cannot be modelled, u_t. Though the individual lagged R and D terms could be included, Lu, Cline and Quance use a thirteen year lag structure for R and D expenditures. The hypothesis that the weights appropriate to the lagged R and D expenditures lie on an inverted U-shape saves ten degrees of freedom and avoids multicollinearity problems. However, if the assumption is false the estimates of the coefficients will be biased and inconsistent.

Another US study by Evenson, Waggoner and Ruttan (1979) regresses productivity change on scientific research, technical research, extension and farmer education. The products of these variables are included in the equations and found to be significant, suggesting that inter-action is important. The studies for other countries add further variety. Doyle and Ridout (1985, p.111) argue that the lag structure used in the American studies leads to the unacceptable consquence that "if expenditure on research declines, the level of productivity is predicted to fall". Instead, their R and D variable is the first difference of the knowledge stock ($K_{t-i} - K_{t-i-1}$), which cannot be negative. Hastings (1981) employs a research index based on numbers of scientists, rather than R and D expenditures. Thus,

(10) $R_{t+1} = R_t(1 + \Delta R_t/R_{t+1})$, where $\Delta R_t/R_{t+1}$ is the proportional change in scientific personnel between successive periods.[10]

None of these approaches is entirely satisfactory, for ideally we should be measuring the <u>output</u> of the R and D industry and including it as the technology input in the production function. Evenson (1982) and Binswanger

(1984) have used patent information as a measure of research output.[11] Mensch (1979) counted the number of "significant" innovations emanating from particular industries, while Evenson and Kislev (1973) used enumeration of scientific journal articles as a measure of agricultural research output. License information has been similarly employed in the measurement of international technology flows.

Where both the output of technology and the R and D expenditures on inputs required to produce it are measurable, it is at least conceptually possible to make technology truly endogenous. The output of technology could appear as an explanatory variable in the production function and as the dependent variable in the "technical change production function".[12]

4) Problems

Though most studies using 1960s data produced apparently sensible results, suggesting a high social rate of return to R and D expenditures, more recent work on the industrial sector (Griliches (1984)) using 1970's data casts doubt on these models. Several separate problems give cause for concern.

(a) Specification eerror and the sources of productivity growth

Changes in total factor productivity may be partially accounted for by science based technical change but there are several other contributary causes. These include the changing composition of the workforce, education, learning by doing, structural change,[13] economies of scale, changes in capacity utilization and institutional change. Dennison (1979) finds "advances in knowledge" to be the most important determinant of productivity change, but R and D is not the only source of advances in knowledge. Indeed, several studies suggest that R and D may account for as little as one-sixth of the total contribution of advances in knowledge. Improvements in managerial and organisational knowledge are just as important as technical information.

Omission of relevant variables can be expected to bias the R and D coefficient upwards.

Lastly, it is often not possible to distinguish between labour (and other inputs) used to produce current output and labour used in research. Equation (1) will be mis-specified unless R and D is performed outside the industry concerned. This is fortunately the case for the majority of agricultural research.

(b) Identification, complementarity and choice of functional form

Even if the relationship between productivity change and the explanatory variable were corrected specified, critics such as Nelson (1981, pp.1054-5) have stressed the complementarity of the causes of growth. Bonnen (1983, p.959) argues that it is not possible to distinguish clearly the marginal returns to complements in production. The rate of return commonly attributed to R and D is actually the product of the interaction between technology, human capital and institutional adaptation. This is corroborated by Evenson, Waggoner and Ruttan (1979), who finds the interactions between scientific research, technical research, extension and farmer operators' education to be important in explaining productivity changes.

A second difficulty is that of distinguishing between factor substitution, technical change and returns to scale. Problems with the neoclassical distinction between factor substitution and technical change have been discussed by Nelson (1980) and Rosenberg (1976). Disentangling technical change and returns to scale has long attracted attention (see Sato 1981 on the "Solow-Stigler" controversy). Sato's (1981) detailed examination provides a clear statement of the underlying difficulty. If technical progress is included in the production function in such a way that it has no effect other than to relabel the isoquants, then the production function is said to be holothetic for that particular representation of technical progress. In such cases, technical change is transformed into a scale effect and cannot be separated from returns to scale.

In the case of a homothetic function such as (4), the exponential time-trend term represents neutral technical change which definitionally leaves the marginal rates of substitution between A, L and K unchanged. The function is holothetic for that representation of technical change. K is also a representation of technical progress, but (4) is strongly separable, so that definitionally, the marginal rate of substitution between A and L is unaffected by K. The function is holothetic under that representation of technical progress as well. It is not possible to distinguish between technical change and returns to scale due to the choice of functional form of the production relationship and the representation of technical change within it.

A separate problem is that if the R and D variable is to be included in a separable function such as a Cobb Douglas, technical change is assumed to be neutral as between all other input pairs.[14] This condition is unlikely to be met in agriculture. For example, Thirtle (1985) shows that in US field crops, mechanical technical change has reduced the labour inputs faster than biochemical technology has reduced the land input.

(c) <u>Appropriability and Spillovers</u>

Griliches (1973, 1979) argues that the social benefit from the introduction of a new or better quality consumer good will be captured only to the extent that the producer has the monopoly power to appropriate the increase in consumer surplus. Where the product innovation is the input in another industry, the productivity gain will be picked up if the value of the output of the user industry is correctly measured. Thus, improvements in agricultural machinery may be partly caught in quality adjusted input series, but productivity gains that are not appropriated by the machinery companies will show up as cost-reducing process innovations in agriculture.

Public sector biological technology is similar, since in the post Rothschild Report political climate, some of the value of innovations will be caught in royalty payments. Further benefits may be appropriated by the private sector seed producers if they have the monopoly power to appropriate productivity gains that the public sector has missed. Any residual benefits will be captured in the increase in agricultural output per unit of inputs.

Agriculture also does well in that it is one of few industries for which the basic research, done by universities and government institutes, that is likely to affect productivity, can actually be identified and taken into account. Even so, there will be positive and negative spillovers, between industries, between crops (or activities), between regions and between countries[15]. Some benefits of UK agricultural R and D will benefit other industries, other crops and foreign nationals. At the same time R and D outside agriculture and agricultural R and D by other countries will produce external economies reflected in UK agricultural productivity. Other effects that are missed by the market, such as environmental degradation (or improvement) should also be included in rate of return calculations.[16]

(d) Econometric Problems

Multicollinearity is a persistent problem caused by the fact that the explanatory variables of interest tend to move together. This adds to the problem of inferring their separate contributions. Since price data tends to be less collinear than inputs, the cost, profit or input demand functions may be preferable to the production function approach which has been used to date.

Griliches (1979) also provides a discussion of the problem of simultaneity in this context and several of the US studies (such as Lu, Cline and Quance 1979) comment on serial correlation and its correction.

(e) Calculating rates of return

The basis of the rate of return calculation is straightforward. In equation (4), for instance, the estimated value of γ is the output elasticity of research capital, which is

$$\frac{\partial Q}{\partial K} \cdot \frac{K}{Q} .$$

Multiplied by the average product of research capital ($\frac{Q}{K}$ calculated as a geometric mean), this gives the marginal physical product, which can be multiplied by the price of the output to give the value marginal product (VMP) of research capital.[17]

Using the value marginal product, the marginal internal rate of return (MIRR) can be calculated from,

$$(11) \qquad \frac{\sum_{i=m}^{n} (VMP)}{(1-r)^{i}} = 0$$

The MIRR is the discount rate (i), that sets the discounted sum of the benefits, occurring from year m to year n, equal to zero.

Davies (1981a)[18] and Wise (1986) both show that there are in fact considerable variations in method of calculation of the MIRR, leading to significantly different outcomes. The main difficulties are; (a) the units of measurement of output value and the cost of research inputs, both of which may be in current or constant dollars; (b) the treatment of private sector research, for which expenditure data are not available; (c) the assumed distribution of the research benefits over time. On (c), assumptions vary from all benefits occurring in year n only, to benefits beginning in year n and continuing into perpetuity (Peterson, 1967). Lu, Cline and Quance (1979) calculate the MIRR on the basis of benefits occurring over the thirteen year lag period, with annual VMPs calculated from the α_i coefficients in equation (9). Their estimated MIRR is 26.5 percent.

5. Conclusion: The Returns to Public Sector Agricultural R and D in the UK

The difficulties in estimating the returns to agricultural R and D are considerable, but several of the problems discussed above are minimised in agriculture relative to the industrial sector. For a start, there is little quality change or new products in agricultural output. This helps to make it possible to pick up product innovations in the agriculture input industries in agricultural productivity calculations. Research is carried on largely outside the farm sector, so the difficulty of separating research inputs from production inputs does not arise.[19] The basic sciences that affect agricultural technology can be identified and hence basic research could in principle be included. Lastly, the spillovers between agriculture and other industries are likely to be lower than for most industries categorised by the SIC code.

At the aggregate level, the study by Doyle and Ridout (1985) is indicative of the research possibilities, but also shows the art to be underdeveloped at present. Several productivity indices for U.K. agriculture are available and they vary considerably (Thirtle, 1986). The public sector R and D expenditure and extension service figures require careful compilation, while little information is available on the activities of the private sector or on basic scientific research. Education should be included and a weather index[20] constructed, based on trial plot yields or actual weather information. A little theoretical ingenuity may allow private (mechanical and chemical) technical change and public (biological) technology to enter the production relationship separately, with non-neutral effects.

One option that minimises the problems involved in establishing the relationship between public sector R and D and agricultural productivty is to resort to crop-specific, trial plot data. This avoids the difficulties of aggregation and the data are far more reliable, with anomalies usually explained. The lack of observations due to the short duration of time series available can be overcome by pooling the different trial plot sites. A further gain is that the lags involved are only those between inception of a research project and the appearance of tangible results at the research institution. Thus, the shortness of the time series available is less of a problem and the added difficulty of modelling the diffusion process is avoided.

For oilseed rape, public sector research began in the early 1970s. The cost of this research is reasonably well documented. Labour input data from 1973 are available for varietal development and disease resistance research conducted at the Plant Breeding Institute (P.B.I.). The numbers and costs of trials conducted at over thirty sites by ADAS from 1973 to 1985 are also available. These could be included separately as explanatory variables (the equivalent of basic and applied research).[21] The trials produce yield data and the crop variety, fertilizer input and information on other chemical applications are also recorded.[22]

These data are sufficient to support a model similar to that of equation (9), such as,

$$(12) \quad Q = Ce^{\delta t}F^{\alpha}A^{1-\alpha} \prod_{i=0}^{m} P_{t-i}^{\alpha i} \prod_{j=0}^{n} T_{t-j}^{\gamma j} e^{w_t u_t}$$

where Q is physical output, C is a constant, δ_t a catch-all time trend, F is fertilizer, A is land, P is PBI research, appropriately deflated, T is the number of trial plots, w_t is the weather index and u_t is a stochastic error term.

Taking logarithms and exploiting the assumption of constant returns to scale[23], equation (12) can be rearranged to give,

$$(13) \quad \ln Q - \ln A = \ln C + \delta_t + \alpha(\ln F - \ln A)$$

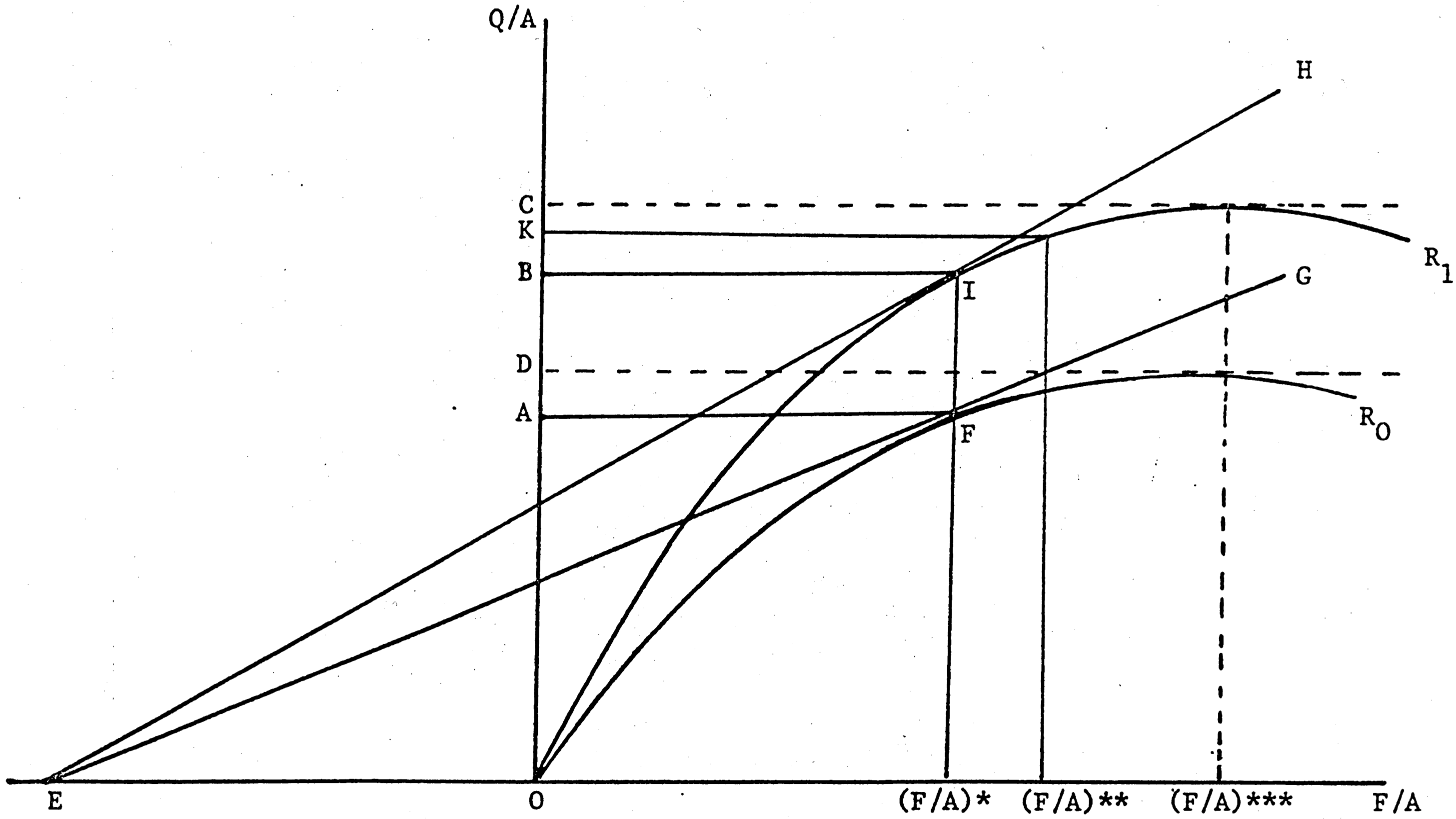
$$+ \sum_{i=0}^{n} \alpha_i \ln P_{t-i} + \sum_{j=0}^{m} \gamma_i \ln T_{t-j} + w_t + u_t$$

Equation (13) suggests that the logarithm of the yield, is explained by an arbitrary constant, a time trend that is a proxy for any missing time - related variables, the logarithm of fertilizer per unit area, the distributed lag structures of PBI and ADAS trial plot research, the weather and a stochastic error.

Obviously variations are possible; a fixed effect model would dispose of yield differences due to missing variable such as soil types, by mean differencing, which would dispose of the constant; if the mis-specification[24] is minimal, the time trend may be insignificant; and the two lagged research variables may be added together. This would give a basic model that claims the relationship between yields and fertilizer per area, lagged research and the weather, to be linear in logarithms.[25] To reduce the dimensions further, suppose that the weather can be regarded as part of the error structure. Then the deterministic model has yield as a function of fertilizer application rates, and is no more than a fertilizer response function. However, research expenditures shift the response function upwards in a Hicks-neutral manner.[26]

This is shown in Figure I, when OR_o represents the response function for the old crop variety and OE measures the ratio of the price of fertilizer to the price of land. Point F, where the line EG is tangential to the response function, determines the economically efficient fertilizer application rate of (F/A)*. At F the value marginal product of fertilizer (the slope of OR_o) is equal to the price of fertilizer relative to the price of the output (the slope of EG). OR_1 represents the response function for a newly developed high-yielding variety. If the ratio of factor prices remains constant and technical change is Hicks neutral, the new equilibrium will be at point I, and the proportional increase in output will be AB/OA. The measure of technical

Figure I : Fertilizer Response and New Technology



change is unambiguous in this instance due to the assumption of Hicks neutrality and the unchanged factor price ratio.

Typically, the price ratio will change between period zero and period one, so that the new tangency may lie at a point such as J. Then, since only points F and J are observable, the total yield increase, AK will be the combined effect of technical change of AB/OA and an increase in fertilizer use from (F/A)* to (F/A)**, which accounts for the remaining yield increase of KB. Solow's (1957) study provides a methodology for estimating the contribution of technical change in these circumstances.

Trial data may be expected to raise a slightly different problem. Since agricultural scientists are not attempting to maximise profits, but instead to investigate the yield potential of crop varieties, they may tend to fertilize up to the point (F/A)***, at which point the biological maximum is achieved. This would give a measure of technical change of CD/OD. Again this measure is unambiguous, but there is no reason to suppose that it will be equal to the measure (AB/OA) that would have been obtained in an economic environment. Thus, to the extent that the scientists conducting the trials treat fertilizer as a free good, the results may be an inaccurate guide to the outcome under commercial agriculture.

The use of the yield as a productivity index in equation (13) is not hard to justify. If the public sector research is aimed at new plant varieties, at modifying cultivation techniques or at more effective disease and pest control, the major effect will be on crop yields, rather than say on labour productivity.[27]

Indeed, the intractable problem of dealing with private sector research is avoided by the assumption that public sector research affects yields whereas private sector research does not.[28] Similarly, the costs of externalities such as damage to the environment can be safely ignored at this stage of the analysis. If, however, a second stage was to be added, investigating the diffusion of trial plot results across the farm acreage, then environmental damages should be included as an additional cost.

In summary, it would appear that although the evaluation of R and D productivity on the basis of trial plot data is more limited than aggregate analysis, it is far more likely to produce results that are not spurious. The range of problems involved in economy or sector-wide studies appear to be sufficiently intractable to make this more limited option an attractive proposition, and work is currently in progress.

NOTES

1. See Fishel (ed.) (1971), Arndt, Dalrymple and Ruttan (eds.) (1977), Peterson and Hayami (1977), Evenson, Waggoner and Ruttan (1979), Scobie (1979), Schuh and Tollini (1979), Norton and Davis (1981), Evenson (1982) and Ruttan (1982).

2. Binswanger (1986) points out that the cost and profit functions provide alternative approaches with different interpretations. Though these functions have frequently been applied to the study of technical change (Thirtle and Ruttan, 1986), they have not been used in evaluating the returns to R and D. However, Nadiri (1980) does estimate input demand functions with this aim in view.

3. See Ruttan (1982), Table 10.3 pp.242-3 for a summary of past studies.

4. Constant returns to scale in the conventional inputs is a common restriction, but is not necessary.

5. If this expression is differentiated with respect to time, we get

   (N.1) $p = \lambda + \gamma k,$

   where p is the rate of growth of total factor productivity and

   $$k = \frac{dK}{dt}\frac{1}{K} = K/K$$

   Since $\gamma = \frac{dQ}{dK} \cdot \frac{K}{Q}$ and $\gamma k = \frac{dQ}{dK} \cdot \frac{K}{Q}\frac{\dot{K}}{K} = \frac{dQ}{dK}\frac{\dot{K}}{Q}$,

   (N.1) can be written as

   (N.2) $p = \lambda + \gamma k = \lambda + \rho I_r/Q$

   where I_r/Q is the ratio of net research investment to total output and ρ is the rate of return on research investments. (Griliches 1973, pp.62-4). While (N.2) appears to be simple and has been used in rate of return calculations (Fellner, 1970), it doesn't avoid the problems that are more apparent in less concise formulations. For a recent application of this type of equation, see Clark and Griliches (1984).

6. Again, constant returns to scale is a convenient but not a necessary assumption. It does allow equation (5) to be simply converted to labour productivity since,

   (N.3) $\ln Q - \ln L = \alpha(\ln A - \ln L) + \gamma \ln K.$

   The formulation has been used by Cuneo and Mairesse (1984). For a productivity index approach that does not assume constant returns see Nadiri and Schenkerman (1981).

7. Griliches (1979, p.99) summarises the neoclassical view. "Conventional productivity measures reflect, (therefore), the cost-reducing inventions made in the industry itself, and the social product of inventions in the input-producing industries which have not already been reflected in the

price of purchased inputs".

8. This simple formulation is not simply of historical interest. Griliches (1980) is a recent application.

9. See also Nadiri (1980), or Suzuki (1985), for simple fixed depreciation models.

10. This approach does avoid the need for a deflator for R and D expenditures. Doyle and Ridout (1985) used the retail price index which obviously has inappropriate weights. For the UK a deflator can be calculated from the 1960s onwards, but is typically available only for every third year.

11. Evenson was mainly interested in patents as a source of information on private sector research, for which little expenditure data is available.

12. This term has been used slightly differently by Sato and Suzawa (1983, p.110) who have productivity change as the dependent variable and R and D and the basic stock of knowledge as explanatory variables, in a Cobb Douglas function,

$$(N.3) \quad \dot{P}/P = CR^{\alpha}B^{\beta},$$

where P is productivity, $\dot{P}$ its time derivative, R is research expenditure and B is basic knowledge. This is little different from the models discussed above.

13. In a single industry, such as agriculture, structural change is replaced by the reallocation of factors from less highly valued to more highly valued activities.

14. Griliches has argued against "fancier" functional forms on the grounds (Griliches, 1973, p.87) that the elasticity of substitution is not of primary interest and that (Griliches 1979) more and better data would be required since more general functions are less parsimonious in parameters.

15. Evenson, Waggoner and Ruttan (1979) produce evidence of regional spillovers in US agriculture.

16. See for example Hightower's (1973) critique of the Land Grant College System, which he sees as obsessed with increasing output without regard to other objectives.

17. For equation (9), the total output elasticity of research expenditures is $\alpha = \prod_{i=0}^{n} \alpha_i$, which is equivalent to γ in equation (4).
This productivity index must also be converted back to a measure of total output.

18. See also Davis (1981b), which compares the consumer plus producer surplus approach and the production function approach to evaluating returns to agricultural research.

19. This is a simplistic view, which ignores "informal", on-farm research. It should be balanced by Evenson's (1982, p.237) estimate that the

typical US family farmer devotes about one quarter of his time to "searching, screening, and experimentation with new technology".

20. Doyle and Ridout (1985) use a weather index based on actual cereal yields, which is then used to explain a productivity index that includes the output of cereals.

21. Farmer education and extension expenditures are obviously not relevant to trial plot data.

22. A disease index is also available, so it is conceptually possible to divide the varietal effects into higher yields per se and better resistance to disease.

23. For trial plot results, this would seem to be a theoretical requirement. Under most other circumstances it is an unwarranted assumptin.

24. Perhaps the major specification error is the spillover from French research on oilseed rape. Conceivably, French research could be included in the equation.

25. Binswanger (1986, p.469) suggests an alternative, arguing that if the value of the change in fertilizer cost were subtracted from the value of the increase in yield, the result would be a measure of the residual profits of land. This implicitly measures technical change as the increase in returns to the fixed factor, which is the profit function approach.

26. Thus the model is equivalent to Solow's (1957) analysis, but with land replacing labour and fertilizer instead of capital.

27. The underlying assumption, frequently used in agricultural economics is that the production function is separable. If,

(N.4) $Q = f(A, F, B; L, M, E)$,

where Q is output, A is land, F is fertilizer, B is public sector (biological) research, L is labour, M is machinery, E is engineering or mechanical (private) research and (;) denotes separability, then it is possible to examine the effect of variables to the left of the semi-colon independently of those to the right.

28. This requires the added assumption that the research undertaken by seed companies, which clearly draws on the public sector output, does not result in any significant feedback to the public sector plant breeders.

REFERENCES

Arndt, T.M., Dalrymple, D.G. and Ruttan, V.W. (eds.) (1977). Resource Allocation and Productivity in National and International Agricultural Research, University of Minnesota Press, Minneapolis.

Binswanger,H.P. (1984). Agricultural Mechanisation - A Comparative Historical Perspective, World Bank Staff Working Paper, No. 673.

Binswanger, H.P. (1986). Evaluating Research System Performance and Targeting Research in Land-abundant Areas of Sub-Saharan Africa, World Development Vol.14, No.4, April, pp.469-475.

Bonnen, J.T. (1983). Historical Sources of US Agricultural Productivity: Implications for R and D Policy and Social Science Research, American Journal of Agricultural Economics, Vol.65, No.5, December, pp.958-966.

Bredahl, M.and W. Peterson (1976). "The Productivity and Allocation of Research: U.S. Agricultural Experiment Stations", American Journal of Agricultural Economics, Vol.58, pp.684-92.

Clark, K.B. and Griliches, Z. (1984). Productivity Growth and R and D at the Business Level: Results from the PIMS Data Base, Ch.19 in Griliches, Z. (ed.), R and D Patents and Productivity, University of Chicago Press, Chicago.

Cline, P.L. and Y.C. Lu (1976). "Efficiency Aspects of the Spatial Allocation of Public Sector Agricultural Research and Extension in the United States". Regional Science Perspectives, Vol.6, pp.1-16.

Cuneo, P. and Mairesse, J. (1984). Productivty and R and D at the Firm Level in French Manufacturing, Ch.18 in Griliches, Z. (ed.) R and D Patents and Productivity, University of Chicago Press, Chicago.

Davis, J. (1981a). A Comparison of Procedures for Estimating Returns to Research Using Production Functions, Australian Journal of Agricultural Economics, 25(1), 60-72.

Davis, J. (1981b). The Relationship between the Economic Surplus and Production Function Approches for Estimating Ex Post Returns to Agricultral Research, Review of Marketing and Agricultural Economics, 49(2), 95-105.

Denison, E. (1979). "Explanations of Declining Productivity Growth", Survey of Current Business, Vol.59, August, pp.1-21.

Doyle, C.J. and Ridout, M.S. (1985). The Impact of Scientific Research on UK Agricultural Productivity, Research Policy, Vol.14, pp.109-116.

Evenson, R.E. (1967). The contribution of agricultural research to production, Journal of Farm Economics, Vol.49(5), pp.1415-25.

Evenson, R.E. (1982). Agriculture, Ch.5 in: Government and Technical Progress, Nelson, R.R. (ed.) Pergamon Press, N.Y.

Evenson, R.E. and Kislev, Y. (1973). Research and Productivity in Wheat and Maize, Journal of Political Economy, Vol.81, Sept-Oct. pp.1309-29.

Evenson, R.E, Waggoner, P.E. and Ruttan, V.W., (1979). "Economic Benefits from Research: An Example from Agriculture". Science, Vol.205, pp.1101-1107.

Fellner, N. (1970). 'Trends in the Activity Generating Technological Progress', American Economic Review, March.

Fishel, W.L. (ed.) (1971). Resource Allocation in Agricultural Research, University of Minnesota Press, Minneapolis.

Griliches, Z. (1964). Research Expenditures, Education and the Aggregate Agricultural Production Function, American Economic Review, Vol. LIV, December, pp.691-74.

Griliches, Z. (1973). Research Expenditures and Growth Accounting, Ch.3 in: Science and Technology in Economic Growth, Williams, B.R. (ed.) Macmillan.

Griliches, Z. (1979). Issues in Assessing the Contribution of R and D to Productivity Growth, The Bell Journal of Economics, Vol.10, No.1, Spring, pp. 92-116.

Griliches, Z. (1980). "R and D and the Productivity Slowdown", American Economic Review, May, pp.343-348.

Griliches, Z. (ed.)(1984). R & D, Patents and Productivity, University of Chicago Press.

Hastings, T. (1981). The Impact of Scientific Research on Australian Rural Productivity, Australian Journal of Agricultural Economics, April, pp.48-59.

Hightower, J. (1973). Hard Tomatoes, Hard Times, Schenkerman, Cambridge, Mass.

Kahlon, A.S., Bal, H.K., Saxena, P.N. and D. Jha. (1977). "Returns to Investment in Research in India", Resource Allocation and Productivity in National and International Agricultural Research, ed. T.M. Arndt, D.G. Dalrymple and V.W. Ruttan, Minneapolis, University of Minnesota Press.

Knutson, M. and L. Tweeten (1979). "Toward an Optimal Rate of Growth in Agricultural Production Research and Extension". American Journal of Agriucltural Economics, Vol.61, pp.70-76.

Lu, Y., Quance, L. and C.L. Liu (1978). "Projecting Agricultural Productivity and Its Economic Impact", American Journal of Agricultural Economics, Vol.60, pp.976-80.

Lu, Y., Cline, P. and Quance, L. (1979). Prospects for Productivity Growth in U.S. Agriculture, Agriculture Economic Report, No. 435, ESCS, USDA, Washington, D.C.

Mensch, G. (1979). Stalemate in Technology: Innovations Overcome the Depression, Ballinger, Cambridge, Mass.

Minasian, J.R. (1969). Research and Development, Production Functions, and Rates of Return, American Economic Review, May, pp.80-85.

Nadiri, M.I. (1980). Contributions and Determinants of Research and Development Expenditures in the US Manufacturing Industries, Ch.5 in von Furstenberg, G. (ed.) Capital, Efficiency and Growth, Ballinger, Cambridge, Mass.

Nadiri, M.I. and Schenkerman, M.A. (1981). Technical Change, Returns to Scale, and the Productivity Slowdown, American Economic Review, Vol.71, No.2, May, pp.314-19.

Nelson, R.R. (1980). Production Sets, Technological Knowledge and Research and Development: Fragile and Overworked Constructs for the Analysis of Productivity Growth, American Economic Review, Vol.70, No.2, May, pp.62-67.

Nelson, R.R. (1981). Research on Productivity Growth and Differences: Dead Ends and New Departures, Journal of Economic Literature, Vol. XIX, No.3, September, pp.1029-1064.

Norton, G.W. and Davis, J.S. (1981). Evaluating Returns to Agricultural Research: A Review, American Journal of Agricultural Economics, Vol.63, November, pp.685-99.

Norton, G.W. (1981). "The Productivity of Research: U.S. Agricultural Experiment Stations, Revisited". North Central Journal of Agricultural Economics, Vol.3, pp.1-12.

Peterson, W.L. (1967). Returns to Poultry Research in the US, Journal of Farm Economics, Vol.49(3), pp.656-99.

Peterson, W. and Hayami, Y. (1977). Technical Change in Agriculture, in Martin, L.R. (ed.), A Survey of Agricultural Economics Literature, 1940-70, Vol.I, University of Minnesota Press, Minneapolis.

Rosenberg, N. (1976). Problems in the Economists' Conceptualization of Technological Innovation, in: Perspectives on Technology, Ch.4, Cambridge University Press.

Ruttan, V.W. (1982), Research Policy, University of Minnesota Press, Minneapolis.

Sato, R. (1981). Theory of Technical Change and Economic Invariance: Application of Lie Groups, Academic Press.

Sato, R. and Suzawa, G.S. (1983). Research and Productivity: Endogenous Technical Change, Auburn House, Boston.

Schuh, G.E. and H. Tollini, (1979). Costs and Benefits of Agricultural Research: State of the Arts. Washington,D.C. World Bank Staff Working Paper No.360.

Scobie, G.M (1979). Investment in International Agricultural Research: Some Economic Dimensions. Washington, D.C. World Bank Staff Working Paper No.361, October.

Solow, R.M. (1957). Technical Change and the Aggregate Production Function. Review of Econ and Stats. Vol.39, August, pp.312-20.

Suzuki, K. (1985). Knowledge Capital and the Private Rate of Return to R and D in Japanese Manufacturing Industries, International Journal of Industrial Organisation, Vol.3, pp.293-305.

Thirtle, C.G. (1985). Induced Innovation in US Field Crops, 1939-78. Journal of Agricultural Economics, January, pp.1-14.

Thirtle, C.G. (1986). Problems in the Definition and Measurement of Technical Change and Productivity Growth in the UK Agricultural Sector, Manchester Working Papers in Agricultural Economics, (WP/03).

Thirtle, C.G. and V.W. Ruttan (1986). The Role of Demand and Supply in the Generation and Diffusion of Technical Change. Univeristy of Minnesota, Economic Development Centre, Spetember.

White, F.C. and Havlicek, J. (1982). Optimal Expenditures for Agricultural Research and Extension: Implications of Underfunding, American Journal of Agricultural Economics, Vol.64, No.1, February, pp.47-55.

Wise, W.S. (1986). The Calculation of Rates of Return on Agricultural Research from Production Functions, Journal of Agricultural Economics, Vol.XXXVII, No.2, May, pp.151-161.