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Explaining Total Factor Productivity Change: Returns to R & D in U.K. Agricultural Research[1]

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Explaining Total Factor Productivity

Change: Returns to R & D in U.K.

Agricultural Research[1]

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*Public sector agricultural research expenditure in the U.K. has been cut drastically over the last few years. A number of estimates of the rate of return to U.K. agricultural R & D suggest that such cuts may well be justified, since from those studies returns appear to be low or even negative. However, this paper shows that these estimates should be carefully scrutinised, since if the standard economic methodology is applied to the U.K. situation, the estimated rate of return may be as high as one hundred percent.*

## I. INTRODUCTION

Public agricultural research institutions in the U.K. date back to the 1840's, when the Agricultural Chemistry Association of Scotland established a laboratory in Edinburgh and Sir John Bennet Laws set up an experiment station on his ancestral estate, at Rothampsted. Government funding began at the turn of the century, quickly leading to grants supporting several institutes and university departments. The Agricultural Research Council (ARC) was established in 1931, initially to fill the gaps between the institutes, and spent a little over six thousand pounds in its first year. Its budget is currently running at around £120 million per annum, despite cuts since 1984 that have reduced real expenditures by over 25%.

The historical precedent for public funding of agricultural research is easy to explain. Nelson (1981, p.1050) points out that farming is the achytypal

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example of a sector in which diffusion is the dominant mechanism for the spread of new technology. Farms are too small (relative to the size of the market) to perform their own R & D[1] and are unable to expand market shares rapidly. In the areas of mechanical and chemical innovations, the majority of R & D has been undertaken by input suppliers, but biological innovations are less easily patentable. Thus, social and private returns diverge in crop and livestock research, which remain primarily public sector activities despite recent "plant breeder's rights" patent legislation intended to improve appropriability of returns to investment in these areas.

Since the Rothschild Report of 1971 raised the issue of value for money in publically funded scientific research, the U.K. Research Councils, like the universities, have come under scrutiny. The need to determine the economic return to research activity may be explained both by the ever increasing cost of research and by the growing knowledge that successful research resource allocation can yield high rewards and significantly affect the country's future.[2] The growing interest in privatisation has added a further dimension to the debate, bringing in the question of the appropriate division between the public and the private sectors. Thus the privatisation of the Plant Breeding Institute (PBI) and the National Seed and Development Organisation (N.S.D.O.) has accompanied considerable reorganisation of the research system (including the contracting out of research projects) and the closure of several institutes controlled by the Agricultural and Food Research Council (A.F.R.C.). The scale of the cutbacks can be seen most clearly in job losses. As of October 1985, the AFRC institutes and units employed a staff of 6,200, but around six hundred posts per year have been lost since 1984/85.

The AFRC (1988) has responded to these developments in its recent corporate plan, which shows high rates of return to some of its investments. Expenditures of £23.84 million are supposed to have produced benefits of £1841 million. While this information is useful, it cannot justify the overall budget and indeed, the government is sufficiently unimpressed to have ordered even larger cuts this year. The Financial Times reported on 7th July, that horticultural research is to be cut by up to 65% from the present total of about £17 million a year.

Arable crop cuts of about 33% or £6 million are proposed over the next three years. Similar cuts are expected for other areas, particularly livestock research. The Minister of agriculture has described claims made by the Institute of Professional Civil Servants, that the cuts amount to £60 million, as exaggerated. Even so, the cuts to date (August) amount to some £30 million, or 20% of the total research budget.

Economists would argue that it is the rate of return to the marginal project, or the marginal pound of expenditure that is relevant to determining the total allocation of resources to agricultural research. Hence this study attempts to calculate the marginal internal rate of return to society of U.K. public sector agricultural research investments over the period 1965-80. First, we consider the literature, which shows considerable disagreement over the validity and usefulness of rate of return calculations.

## II. THE CURRENT DEBATE

Two basic methodologies have dominated the calculation of returns to agricultural research. Ex-post cost-benefit analysis (confusingly called the index number approach in the American literature) has been extensively employed to calculate the net benefits to consumers and producers, using a supply and demand framework. Alternatively, production functions have been fitted, with a view to identifying the returns to the R & D input. The CBA studies tend to be of individual inventions or single crops, whereas the production function analyses are usually at a higher level of aggregation. However, either technique may be employed at any level of aggregation. The results of most studies conducted internationally before 1980 are reported in Ruttan (1982) and in several other publications. Over thirty studies of each type are consistent in showing internal rates of return mostly between thirty and sixty percent. Table I updates Ruttan's information from 1980 to the present, and seems to show that although recent studies make less impressive claims, returns still tend to exceed normal rates of return on public funds, EXCEPT in the U.K. where some studies show returns to be very low, or even negative.

Excepting the U.K. studies, these high social rates of return seem to emerge regardless of methodology, level of aggregation or geographical area and this consistency has been taken by most American agricultural economists as evidence of "persistent underinvestment in agricultural research".[3] Perhaps because of the mingling of economists and scientists in the Land Grant College system, the agricultural research community has assimilated the economists and their views, which have been published in scientific journals. (See Evenson, Waggoner and Ruttan, 1979, for an example, which also references the studies in Table I prior to 1981). As a result, when the U.S. agricultural research establishment came under fire, the agricultural economics profession were able to provide a conceptual and intellectual framework, backed by a large body of empirical evidence, that proved sufficient to explain to the critics why many of their views were misguided.[4] The extent of this success can be judged by the "special case" status granted to agriculture by the political advisers, in the Congress of the United States, Office of Technology Assessment (1986) report, that is otherwise extremely critical of economic evaluations of public R & D.

In Britain, the few economist's contributions to the debate have been more sceptical[5] and have failed to impress the agricultural scientists. The pervasive view has been that associated with the AFRC, frequently expressed by Wise, who has stressed the inaccuracy of CBA studies (Wise, 1975, 1981, 1984) and has recently extended his critique to production function analysis. His conclusions (Wise, 1986, p.159-60) appear to be both that the returns to agricultural research cannot be meaningfully measured by the methods used by economists and that returns to agricultural R & D are as low as 12-16%. These results are reported by Harvey (1987) who goes further, presenting figures that suggest that the current rate of return lies between -37.5% and +4%. Harvey (1988, p.83), goes further still, calculating benefits to be between £165 million and £283 million, as compared with costs of £340 million. Doyle and Ridout (1985) follow a methodology close to that developed by economists, arriving at an average rate of return of between 20% and 30% for 1966-70, but declining to 10-20% by 1978-80.

In order to examine these unusually pessimistic results, the production function approach to the evaluation of R & D is outlined next, followed by a

**Table I : Summary Studies of Agricultural Research Productivity**

| Study | Year | Country | Commodity | Time Period | Annual Internal Rate of Return (%) |
|---|---|---|---|---|---|
| **(A) Cost Benefit Analysis** | | | | | |
| Griliches | 1958 | USA | Hybrid Corn | 1940-55 | 35-40 |
| Griliches | 1958 | USA | Hybrid sorghum | 1940-57 | 20 |
| Grossfield & Heath | 1966 | UK | Mechanical Potato Harvester | 1950-67 | Positive and substantial |
| Peterson | 1967 | USA | Poultry | 1915-60 | 21-25 |
| Evenson | 1969 | S.Africa | Sugarcane | 1945-62 | 40 |
| Barletta | 1970 | Mexico | Wheat | 1943-63 | 90 |
| Barletta | 1970 | Mexico | Maize | 1943-63 | 35 |
| Ayer | 1970 | Brazil | Cotton | 1924-67 | 77+ |
| Schmitz & Seckler | 1970 | USA | Tomato harvester, with no compensation to displaced workers | 1958-69 | 37-46 |
| | | | Tomato harvester, with compensation of displaced workers for 50% of earnings loss | | 16-28 |
| Ayer and Schuh | 1972 | Brazil | Cotton | 1924-67 | 77-110 |
| Hines | 1972 | Peru | Maize | 1954-67 | 35-40 |
| | | | | | 50-55 |
| Hayami and Akino | 1977 | Japan | Rice | 1915-50 | 25-27 |
| Hayami and Akino | 1977 | Japan | Rice | 1930-61 | 73-75 |
| Hertford, Ardila, Rocha and Trujillo | 1977 | Columbia | Rice | 1957-72 | 60-82 |
| | | | Soybeans | 1960-71 | 79-96 |
| | | | Wheat | 1953-73 | 11-12 |
| | | | Cotton | 1953-72 | none |
| Pee | 1977 | Malaysia | Rubber | 1932-73 | 24 |
| Peterson & Fitzharris | 1977 | USA | Aggregate | 1937-42 | 50 |
| | | | | 1947-52 | 51 |
| | | | | 1957-62 | 49 |
| | | | | 1957-72 | 34 |
| Wennergren and Whitaker | 1977 | Bolivia | Sheep | 1966-75 | 44 |
| | | | Wheat | 1966-75 | -48 |
| Pray | 1978 | Punjab (British India) | Agricultural research and extension | 1906-56 | 34-44 |
| | | Punjab (Pakistan) | Agricultural research and extension | 1948-63 | 23-37 |
| Scobie & Posada | 1978 | Bolivia | Rice | 1957-64 | 79-96 |
| Pray | 1980 | Bangladesh | Wheat and Rice | 1961-77 | 30-35 |
| Pray | 1983 | Punjab (British) | Agricultural research and extension | 1930-47 | over 30 |
| | | Punjab (Pakistan) | Agricultural research and extension | 1947-75 | over 30 |
| Casimiro Herruzo | 1985 | Spain | Rice | 1941-80 | 15.9-18.1 |
| Ulrich, Furtan and Schmitz | 1986 | Canada | Malting Barley | 1951-88 | 31-75 |
| Unnevehr | 1986 | S.E.Asia | Rice quality | 1983,84 | 29-61 |
| Furtan & Ulrich | 1987 | Canada | Rape seed | Ex-ante | 51 |
| Norton, Ganoza and Pomereda | 1987 | Peru | Rice | 1981-1996 | 17-44 |
| | | | Corn | " | 10-31 |
| | | | Wheat | " | 18-36 |
| | | | Potatoes | " | 22-42 |
| | | | Beans | " | 14-24 |
| | | | Aggregate | " | 17-38 |
| Harvey | 1988 | U.K. | Agricultural research and extension | Present | -37.5 to +4 |
| Power and Russell | 1988 | U.K. | Poultry feeding research | Present | Benefit/ Cost ratio of 10-78 |
| Beck | 1988 | U.K. | Horticultural Crop Protection | 1979-2001 | 50 |
| | | | Hybrid Sprouts | 1979-2000 | 22 |

(B) Production Function Analysis

| Study | Year | Country | Commodity | Time Period | IRR % |
|---|---|---|---|---|---|
| Tang | 1963 | Japan | Aggregate | 1880-1938 | 35 |
| Griliches | 1964 | USA | Aggregate | 1949-59 | 35-40 |
| Latimer | 1964 | USA | Aggregate | 1949-59 | not significant |
| Peterson | 1967 | USA | Poultry | 1915-60 | 21 |
| Evenson | 1968 | USA | Aggregate | 1949-59 | 47 |
| Evenson | 1969 | S.Africa | Sugarcane | 1945-58 | 40 |
| Barletta | 1970 | Mexico | Crops | 1943-63 | 45-93 |
| Duncan | 1972 | Australia | Pasture Improvement | 1948-69 | 58-68 |
| Evenson and Jha | 1973 | India | Aggregate | 1953-71 | 40 |
| Cline (revised by Knutson and Tweeten, 1979) | 1975 | USA | Aggregate | 1939-48 | 41-50 |
| | | | Research and extension | 1949-58 | 39-47 |
| | | | | 1959-68 | 32-39 |
| | | | | 1969-72 | 28-35 |
| Bredahl & Peterson | 1976 | USA | Cash grains | 1969 | 36 |
| | | | Poultry | 1969 | 37 |
| | | | Dairy | 1969 | 43 |
| | | | Livestock | 1969 | 47 |
| Kahlon, Bal, Saxena and Jha | 1977 | India | Aggregate | 1960-61 | 63 |
| Evenson and Flores | 1978 | Asia-national | Rice | 1950-65 | 32-39 |
| | | | | 1966-75 | 73-78 |
| | | Asia-International | Rice | 1966-75 | 74-102 |
| Flores, Evenson and Hayami | 1978 | Tropics | Rice | 1966-75 | 46-71 |
| | | Philippines | Rice | 1966-75 | 75 |
| Nagy and Furtan | 1978 | Canada | Rapeseed | 1960-75 | 95-110 |
| Lu, Quance and Liu | 1978 | USA | Research and Extension | 1939-72 | 25 |
| | | | Increments in R & E | | 10-15 |
| Lu, Cline and Quance | 1979 | USA | Research and Extension | 1939-48 | 30.5 |
| | | | | 1949-58 | 27.5 |
| | | | | 1959-68 | 25.5 |
| | | | | 1969-72 | 23.5 |

| Study | Year | Country | Commodity | Time Period | Annual Internal Rate of Return |
|---|---|---|---|---|---|
| Davis | 1979 | USA | Aggregate | 1949-59 | 66-100 |
| | | | | 1864-74 | 37 |
| Evenson | 1979 | USA | Aggregate | 1868-1926 | 65 |
| | | USA | Technology oriented | 1927-50 | 95 |
| | | USA | Science oriented | 1927-50 | 110 |
| | | USA | Science oriented | 1948-71 | 45 |
| | | Southern USA | Technology oriented | 1948-71 | 130 |
| | | Northern USA | Technology oriented | 1948-71 | 93 |
| | | Western USA | Technology oriented | 1948-71 | 95 |
| | | USA | Farm management research and agricultural extension | 1948-71 | 110 |
| Hastings | 1981 | Australia | Increases in Research activity | 1926-68 | Increasing Returns |
| White & Havlicek | 1982 | USA | Research and Extension | 1943-77 | 6.9-36 |
| Doyle and Ridout | 1985 | UK | Research expenditures | 1966-70 | 20-30 |
| | | | | 1971-75 | 15-25 |
| | | | | 1978-80 | 10-20 |
| Khan and Akbari | 1986 | Pakistan | Research and Extension | 1955-81 | 36 |
| Wise | 1986 | U.K. | Research expenditures | Present | 15-8 |
| Boyle | 1986 | Eire | - " - | 1963-83 | 26 |
| Tung and Strain | 1987 | Canada | Research expenditures | 1961-80 | High |
| Sumelius | 1987 | Finland | Public Research expenditures | 1950-84 | 25-76 |
| Widmer, Fox and Brinkman | 1988 | Canada | Beef Cattle Research | 1968-84 | 63 |
| Thirtle and Bottomley | 1988 | U.K. | Agricultural research | 1950-81 | 70 |
| Russell and Thirtle | 1988 | U.K. | Rape seed Research | 1976-85 | Benefit/ Cost Ratio 327 |

Source: Ruttan (1982), who gives references. Added items only are referenced in this paper.

discussion of the U.K. data.

## III. THE CONVENTIONAL MODEL

Early empirical work in production economics attempted to explain changes in aggregate output by assuming it to be a log-linear function of aggregate capital and aggregate labour. The history of the subject and the fact that econometricians usually do not collect their own data[6] has led to the misconception that aggregation and the fitting of production functions are separate activities. In fact, index procedures used in aggregation correspond to particular restricted functional forms.[7] The general problem is to reduce m outputs and n inputs to h groups of outputs (often one) and k groups of aggregate inputs. For consistent aggregation, the input groups must be functionally separable.[8]

Since technical change, resulting from R & D expenditures, occurs over time and its effect on output is subject to considerable lags, time series data are required. Since time series data for agricultural inputs are collinear, the number of inputs groups must be restricted and even then, if the full production function is fitted, parameter estimates for inputs which account for minor proportions of output may not be robust. This problem has been circumvented in the recent literature by dividing the inputs into two groups, conventional and novel, and disposing of the conventional inputs by incorporating them in a total factor productivity (TFP) index.[9] Then, changes in the productivity index should be explained by the non-conventional inputs such as R & D expendiures. Following the literature, in using the Cobb Douglas function, if $Q_t$ is aggregate output, (composed of outputs $q_{ht}$), the $x_{it}$'s are traditional inputs and the $Z_{jt}$'s are novel inputs and the $\alpha_i$'s and $\beta_j$'s are parameters, then, the production function can be written,

$$(1) \quad Q_t = \prod_{i=1}^{m} x_{it} \quad \prod_{j=1}^{n} Z_{jt}$$

If the Divisia[10] index is used to aggregate the outputs $q_{ht}$ and the conventional inputs $x_{it}$ then,

$$(2)\quad \ln(TFP_t/TFP_{t-1}) = \tfrac{1}{2}\sum_h (R_{ht} + R_{h,t-1}) \ln (q_{ht}/q_{h,t-1}) - \tfrac{1}{2}\sum_i (S_{it} + S_{i,t-1}) \ln (x_{it}/x_{i,t-1})$$

where the $q_h$ are output indices, the $x_i$ are input indices, the $R_h$ are output revenue shares and the $S_i$ are input cost shares.

Then equation (1) can be written in TFP form, as,

$$(3)\quad \ln P_t = \ln(TFP_t/TFP_{t-1}) = \ln\left(\prod_{j=1}^{n} Z_{jt}^{\beta_j}\right)$$

The $x_i$'s include all conventional inputs such as land, labour, capital, machinery, buildings, chemicals and other miscellaneous inputs. The $z_i$'s are normally the stock of knowledge, K, (accumulated research capital), extension services (X) and farmer education (E). Other variables could be included here. For example Evenson and Kramer (1988) include farm size, farmer's age and the degree of specialisation of farms, all of which are taken to be influenced by agricultural policies that indirectly influence productivity growth. However, any such additions are somewhat ad hoc and do not necessarily represent a more correct specification.

Accumulated research capital (K), could be defined very simply as the sum of past R & D expenditures,

$$(4)\quad K_t = \sum_{i=1}^{n} R_{t-i}$$

but if there is no research, there should be negative growth of $K_t$.[11] The alternative to including an arbitrary depreciation factor in the calculation of $K_t$ is to include a finite number of lagged $R_{t-i}$'s as explanatory variables. Initially, the effect of R & D on productivity is expected to be small and then to rise to a peak, before diminishing to zero as the new technology becomes obsolete.[12] Following this procedure and adding a constant (A) and a stochastic error terms gives the "conventional" model,

$$(5)\quad P_t = A \prod_{i=0}^{n} R_{t-i}^{\alpha_i} X^{\beta_1} E^{\beta_2} e^{\beta_3 W_t u_t}$$

where $P_t$ is the productivity index $W_t$ is a weather index that explains a proportion of the variations in the TFP index, $(P_{t})$ and $u_t$ is the remaining stochastic error that cannot be accounted for.

Taking logarithms of (4) gives the conveniently linear equation,

$$(6) \quad \ln P_t = \ln A + \sum_{i=0}^{n} \alpha_i \ln R_{t-i} + \beta_1 \ln X + \beta_2 \ln E + \beta_3 W_t + u_t$$

However, the dozen or so lagged values of R are likely to be highly correlated and to use up too many degrees of freedom, so a distributed lag structure is often assumed. This is normally an inverted V or an Almon polynomial lag. 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), Evenson, Waggoner and Ruttan (1979) and White and Havlicek (1982), to Australian data by Hastings (1981) and to UK agriculture by Doyle and Ridout (1985).

## IV. THE DATA

Estimation of equation (6) requires a total factor productivity index for the agricultural sector, a weather index and data on research and development expenditures, extension expenditures and farmer education. These are considered in turn.

1) Productivity indices. No up-to-date total factor productivity index for the U.K. is available from official sources, but several attempts have been made to correct this deficiency. Doyle and Ridout (1985) calculated their own arithmetic index for a study similar to this. Whittaker's (1983) Tornqvist and arithmetic indices, based on input definitions close to those used by the Ministry, are published in Rayner, Whittaker and Ingersent (1986). Lastly, Godden (1985) reports Tornqvist and arithmetic indices which make attempts at quality adjustment of the land and capital inputs in particular. All of these alternatives have some attractive features, so all were tried in the analysis.

2) R & D expenditures. After experimentation with AFRC expenditure data,[13]

and with R & D statistics published in Parliamentary Papers, we concluded that the R & D expenditure series used by Doyle and Ridout (1985) could not be at all easily improved upon. We did deflate their series with the Business Monitor "implied deflator for R & D expenditure", (HMSO, 1983) representing the price of scientific manpower, which is more appropriate than Doyle and Ridout's deflator which was the RPI. Unfortunately, this index is available only at three yearly intervals, since 1964. As the expenditure data extend back to 1951 the RPI deflator had to be used for the early observations. Also, although scientific manpower is the largest item of research expenditure, the price of land and buildings and of equipment should also be included. For US agricultural research, a deflator of this type has been constructed by Pardey, Craig and Hollaway (1987), who also discuss the errors caused by inappropriate deflators. Due to these difficulties, series using both the RPI and the implied R & D deflator were tried in estimating the model.

3) The Weather. Three approaches were used to account for the effects of the weather. Including individual rainfall and temperature observations in the regressions proved too costly in terms of degrees of freedom. The obvious choice of a yield index, (see Stallings, 1960) constructed from experiment station data proved to be impossible with the limited National Institute for Agricultural Botany data at our disposal, but should be further investigated. We settled for the third alternative, of a weather index, constructed from precipitation and temperature data, in the manner first suggested by De Martonne (1936). It is based on the formula, $I = P/(T+10)$ where I is the index, P is precipitation and T is the temperature.

4) Farm Education. The variable used in the US studies, farmer's years of schooling, was not available. Instead, we took the ratio of students taking higher education courses in agriculture (reported by Burrell, Hill and Medland, 1984) to the total farm population. A considerable proportion of such students in the UK are from farm families and do enter the industry. This ratio appeared to perform better than years of schooling for the UK population in aggregate,[14] but again, alternatives should be considered.

5) Extension Expenditures. The U.K. extension service, run by the Agricultural

Development Advisory Service, does not publish data series on expenditures or personnel.[15] Although this variable was omitted in parameter estimation, assuming it to be collinear with research expenditures, data for 1983/4 from MAFF (1984) were used in calculating rates of return.

## V. PROBLEMS OF ESTIMATION

Omitting the variable X in equation (6) leaves the equation,

$$(7) \quad \ln P_t = \ln A + \sum_{i=0}^{n} \alpha_i \ln R_{t-i} + \beta_1 \ln E + \beta_2 W_t + u_t \quad ,$$

to be fitted to between fifteen to seventeen annual observations according to which productivity index is used.[16] Since the R & D data extends back to 1951, this allows for a fourteen year lag. Even so, the lack of observations imposed limitations on the analysis. The most obvious problems are considered below.

### 1) The Lag Structure

With more and better data Pardey & Craig (1988) have investigated the appropriate length of the lag and Shiller (1973), and Kashyap and Swamy, Mehta and Parker (1984) have suggested methods of endogenously determining the appropriate shape of the lag structure. Here an Almon polynomial lag was imposed. This can be justified only by the fact that the lag between research expenditures and productivity has been heavily researched, both by gathering information from agricultural scientists and by fitting lag structures to far better data than is available in this instance. The majority of recent studies have opted for a second degree polynomial, rising to a maximum after between six and ten years (Lu, Cline and Quance (1979), Evenson, (1982)).

### 2) Choice of Model

Experimentation to determine the degree of the polynomial and the length of the lag would alone raise the issue of choice between models. But equation (6) was also fitted[17] for all five TFP indices, with R & D deflated by either the price of scientists series or the retail price index. Significance of parameter estimates, goodness of fit, values of summary statistics and conformity to a priori beliefs proved to be an inadequate basis for discriminating between models, so the forecasting ability of the models was used to supplement these criteria.

3) Collinearity

Education was sufficiently collinear[18] with the lagged R & D expenditures, to give inconsistent results, which could be corrected only by crude methods. Education lagged three periods, was regressed on lagged R & D expenditures and the residuals retrieved. These residuals, which could be called "R & D free" education were successfully included in equation (7).

## VI. RESULTS

For each of the five indices, one of the more successful equations has been reported. In each case, a second degree polynomial with a twelve period lag proved as good as any of the alternatives. The "price of scientists" deflator also consistently gave better results than the retail price deflator. The results are reported in Table II. The parameter estimates for the distributed lag coefficients (the $\alpha_i$'s) are the output elasticities of the R & D variable for each year of the lag. The lags are symmetric, inverted U shapes, with the effect of R & D on the productivity index rising to a maximum of between 0.04 and 0.05 and declining again to zero. In all cases, the coefficients of the R & D variable are significant, as is indicated by the t-statistics reported below the lags.

The total effect of R & D expenditure can be judged by looking at the sum of the annual effects ($\Sigma\alpha_i$) over the full period of the lag. Thus, for all the TFP indices, a 1% increase in the R & D variable will increase TFP by between 0.25% and 0.44%. The education variable is significant only for Whittaker's Tornqvist index and the weather variable proved to be insignificant in all the better equations. The adjusted $R^2$ values, reported in the next row, suggest that the variables explain over 75% of the variance in the TFP index. Finally, the Durbin Watson statistic is in the acceptance region only for Whittaker's Tornqvist index. So, in four out of the five cases the alternative hypothesis of serial correlation, either positive or negative, cannot be conclusively rejected.

Table II : Econometric Estimates of the R & D and Weather Coefficients

| Coefficients of Independent Variables | | Dependent Variables - TFP Indices: Godden Quality Adjusted | Godden partially Adjusted | Whittaker Tornqvist | Doyle & Ridout | Whittaker Arithmetic |
|---|---|---|---|---|---|---|
| Distributed lag coefficients, $\alpha_1$ (years, n=0-15) | 0 | 0.0084 | 0.0073 | 0.0096 | 0.0126 | 0.0080 |
| | 1 | 0.0155 | 0.0134 | 0.0178 | 0.0233 | 0.0166 |
| | 2 | 0.0212 | 0.0184 | 0.0245 | 0.0320 | 0.0228 |
| | 3 | 0.0251 | 0.0224 | 0.0294 | 0.0388 | 0.0276 |
| | 4 | 0.0280 | 0.0251 | 0.0334 | 0.0436 | 0.0310 |
| | 5 | 0.0309 | 0.0268 | 0.0356 | 0.0465 | 0.0331 |
| | 6 | 0.0315 | 0.0274 | 0.0364 | 0.0475 | 0.0338 |
| | 7 | 0.0309 | 0.0268 | 0.0356 | 0.0465 | 0.0331 |
| | 8 | 0.0290 | 0.0251 | 0.0334 | 0.0436 | 0.0310 |
| | 9 | 0.0258 | 0.0224 | 0.0297 | 0.0388 | 0.0276 |
| | 10 | 0.0212 | 0.0184 | 0.0245 | 0.0320 | 0.0228 |
| | 11 | 0.0155 | 0.0134 | 0.0178 | 0.0233 | 0.0166 |
| | 12 | 0.0084 | 0.0073 | 0.0096 | 0.0126 | 0.0090 |
| Sum of lag coefficients( $\Sigma \alpha_1$) | | 0.29291 | 0.25427 | 0.33770 | 0.44078 | 0.31376 |
| t Statistics for the lag | | 8.5402 | 7.200 | 6.8725 | 10.0504 | 7.7531 |
| Education coefficients | | 0.0906 | 0.0594 | 0.4947 | 0.1327 | -0.0775 |
| t Statistics | | 0.8826 | 0.5623 | 4.3786 | 1.0823 | -0.5699 |
| Weather coefficients | | 0.0007 | 0.0008 | 0.0005 | 0.0024 | 0.0006 |
| t Statistics | | 0.6938 | 0.6877 | 0.3742 | 1.5869 | 0.5421 |
| Adjusted $R^2$ | | 0.8251 | 0.7659 | 0.7854 | 0.8627 | 0.8251 |
| Durbin-Watson Statistic | | 1.3781 | 1.3110 | 2.1655 | 1.0653 | 1.5294 |

The superiority of Whittaker's Tornqvist index was confirmed by having the model forecast the final TFP observations, using the technique suggested by Salkever (1976). The last three, four and five observations were forecast for all models, and whereas the forecast errors were significantly different from zero for some lag lengths in all the other models, the Whittaker Tornqvist index model performed well over a wide range of lags. For the twelve period lag model, all the forecast errors were very small (reaching a maximum of 0.05) and were insignificantly different from zero (maximum t statistic of 0.85). Forecasting the last five observations, the forecast error changed signs three times, showing a lack of trend. The superiority of Whittaker's index is actually not too surprising, since it was the product of two years work that earned an M.Phil, whereas the other indices were small parts of other projects.

The estimated output elasticities ($\alpha_i$) for the R & D input can now be used to calculate the marginal social internal rate of return to R & D.

## VI. CALCULATION OF THE MARGINAL INTERNAL RATE OF RETURN[19]

The estimates of the previous section suggest that a 1% increase in the R & D input results in an increase in TFP of 0.25% to 0.44%. This increase in TFP must be converted into a rise in the value of output, before the internal rate of return to R & D expenditures can be calculated.

Each lag coefficient $\alpha_i$, is the output elasticity of R & D for that year, which may be defined as,

$$(8) \qquad \alpha_i = \frac{\partial \log P_t}{\partial \log R_{t-i}} = \frac{\partial P_t}{\partial R_{t-i}} \cdot \frac{R_{t-i}}{P_t}$$

Obviously, the marginal physical product of R & D can be expressed as the elasticity multiplied by the average physical product,

$$(9) \qquad \frac{\partial P_t}{\partial R_{t-i}} = \alpha_i \left(\frac{P_t}{R_{t-i}}\right)$$

Replacing $P_t/R_{t-i}$ by the geometric means of these variables over the period under consideration and changing to discrete approximations gives,

$$(10) \qquad \frac{\Delta P_t}{\Delta R_{t-i}} = \alpha_i \left(\frac{\bar{P}}{\bar{R}_{t-i}}\right)$$

Then, the change in productivity can be converted into the change in the value of output if both sides of equation (10) are multiplied by the average net increases in the value of output (Y) caused by a one index point increase in productivity.

$$(11) \qquad \frac{\Delta P_t}{\Delta R_{t-i}} \frac{\Delta Y_t}{\Delta P_t} dP_t = \alpha_i \left(\frac{\bar{P}}{\bar{R}_{t-i}}\right) \frac{\Delta Y_t}{\Delta P_t} dP_t$$

Then the value marginal product of R & D in perod t-i may be written as,

$$(12) \qquad VMP_{t-i} = \frac{\Delta Y_t}{\Delta R_{t-i}} = \alpha_i \left(\frac{\bar{P}}{\bar{R}_{t-i}}\right) \frac{\Delta Y_t}{\Delta P_t}$$

which is the value marginal product (VMP) of R & D at time t-i. Note that the terms $\bar{P}/\bar{R}_{t-1}$ and $\Delta Y_t/\Delta P_t$ are averages but that $\alpha_1$ varies over the lag period, giving a series of marginal returns resulting from a unit change in R & D expenditure. The value of output,[20] $\Delta Y_t/\Delta P_t$, is the geometric mean calculated using the value of output at constant 1975 prices and $\bar{P}/\bar{R}_{t-1}$ is similarly a constant-price geometric average.

Using equation (12), allows the marginal internal rate of return (MIRR) can be calculated, from equation (13),in which n is the length of the lag and the MIRR is equal to r. Hence,

$$(13) \quad \sum_{i=1}^{n} [VMP_{(t-1)}/(1+r)^1] - 1 = 0$$

Performing these calculations for the five equations reported in Table II produces the result in Table III. Only the rate of return for the model using Whittaker's Tornqvist index will be used in further calculations, but the other results are included to give some idea of the likely magnitude of the errors involved in calculating the marginal internal rate of the return (MIRR). A main source of variation in the literature is clearly the estimation of the output elasticity of R & D expenditures. These estimates range from 0.01 to 0.51, which gives little cause for confidence. The exact shape of the lag structure does not appear to be a major cause of variation. Thirtle and Bottomley (1988)

Table III : Marginal Internal Rates of Return

| | Godden Quality Adjusted | Godden Partially Adjusted | Whittaker Tornqvist | Doyle & Ridout | Whittaker Arithmetic |
|---|---|---|---|---|---|
| MIRR | 95% | 74% | 100% | 99% | 85% |

compared the second degree polynomial lag structure with two alternative schemes for fitting inverted V shaped lags and found the variation in MIRR's to be less than 20%.

A further potential source of errors, which may be serious, has been raised by Wise (1986), who argues that should be a lead time of five years before returns begin at all. Though the figure of five years is entirely arbitrary and is not at all supported by the literature, some care is requied. The problem is to determine the lag between expenditure and productivity change for the average dollar of R & D and extension expenditures.

Evenson (1982, p.261) interprets the existing studies as suggesting that, "the effect of research on production begins to be observed about two years after the research investment is made. The effect then rises to a maximum approximately six to ten years after the investment".

Inclusion of extension expenditures may be sufficient to justify no lead time at all. However, if this is an error, discounting all of the benefits stream by an extra two or three years does have a marked effect on returns. For example, re-estimating the best model repoted above, with a three year lead time gave the results reported in Table IV.

Table IV : Varying the Start Point of the Lag Structure

| Lead Time Before Returns Begin (Years) | Sum of the Lag Coefficients ($\Sigma\alpha_i$) and t Statistic | Lag Length (Years) | Adj. $R^2$ | Durbin Watson | Return (MIRR) |
|---|---|---|---|---|---|
| 3 | 0.3729 | 12 | 0.7116 | 1.9004 | 59% |

Lastly, the rates of return reported above rests on several calculations that have not been made explicit. The R & D expenditure series used is for AFRC expenditures and those of the Scottish research institutes. Expenditures for Northern Ireland are negligible, but MAFF in house research expenditure amounted to 36% of the AFRC budget in 1983/4 and the Agricultural Development Advisory Service (ADAS) extension budget was 31% of the AFRC total (MAFF 1984). These proportions were assumed to have remained constant over the period and the series was grossed up to include them. Obviously, this amounts to assuming that these expenditures are exactly collinear with the AFRC R & D expenditures. While this is not true, they are of the right magnitude and hence are included in the MIRR calculation. A further correction is required since private sector research expenditures are probably greater than those of the public sector and that only a proportion of the benefits are both appropriated and captured as quality adjustments in the series for agricultural inputs. To allow for this Evenson (1968) divided his estimated IRRs by a factor of 1.22. The number is arbitrary in this case and we have grossed up the AFRC series by 40%. This is actually 24% of the total public expenditures.

## VII. COMPARISON WITH OTHER RESULTS AND APPRAISAL

Before moving on to more sophisticated estimates, the results of the previous section can be compared with "back of the envelope" calculations of the type reported by Harvey (1987, p.4). Godden's (1985) estimates of TFP growth for the UK agricultural sector are all around 2% as is Rayner, Whittaker and Ingersent's (1986) figure for the 1970's. Zanias (1987) produced a slightly lower estimate of Hick's neutral technical change of 1.7% for the period 1949-83. This is also the annual average growth rate of Doyle and Ridout's (1985) productivity index from 1951-81. All these numbers are arbitrary in the sense that they depend on particular definitions and procedures, but all suggest a number a little below 2%. Hence Harvey (1987) opts for a figure of 1.9%.

To convert this estimate of productivity growth into a value, Harvey (1987) multiplies it by the 1985 <u>net product</u>[22] of U.K. agriculture of £4000 million. But the TFP index is <u>not</u> net of intermediate inputs and capital services. As equation (2) and the associated discussion showed, the TFP was the ratio of total aggregate output to all the conventional inputs. It is compatible with <u>final output</u>, which at £11,000 million gives a return of £220 million on the AFRC investment of £120. This gives a return on capital of 83% instead of the negative value suggested by Harvey.[23] Definitionally, <u>net product</u> excludes intermediate inputs and capital and so corresponds fairly closely to a labour productivity index. Rayner, Whittaker and Ingersent's (1986) annual growth rate of labour productivity is 4.8%. Now if this figure is multiplied by the net product of £4000 million it gives a value of £192 million, for a return of 60%.

Whereas Harvey avoids estimation by using existing productivity indices, Wise (1986) borrows the estimated output elasticity for agricultural R & D from the American literature. He claims that the value used, of 0.06, is "near the upper limit" and this leads to his estimated rate of return of 12-16%. Even if the use of a parameter for another country and another time period could be defended, a passing acquaintance with the literature would reveal the highly regarded work of Evenson (1968). His estimate of $\Sigma\alpha^1$, using a 7½ year lag was 0.21 for a Cobb Douglas production function and 0.51 when the dependent variable was a productivity index, as in this study. If Wise had used these figures, which seem just as suitable as the number he did choose, his rate of return would rise to 42-56% or 102-136%.

Doyle and Ridout's (1985) study merits more careful consideration since they fitted an equation similar to (5) above. They regressed a TFP index on a second degree polynomial lag distribution of the logarithm of R & D expenditures and a weather index. Their R & D and weather parameter estimates were significant and the $R^2$ was 0.844, suggesting that the variables explain 85% of the variance in TFP. Subject to various assumptions as to the level of private sector R & D, the internal rate of return estimates varied from 10% to 30% and declined over time.

Unfortunately, their study suffers from several problems. As they point out themselves (p.115), the diminishing returns to agricultural research expenditures results directly from the fact that they have regressed their productivity index (not logged) index on the logarithm of R & D expenditures, because this "relationship was dictated by the data". Their high level of explanatory power is also suspect since it can in part be attributed to their weather index, which is based on the actual variation in yields of U.K. cereal crops.[24]

There are also several problems of a lower order of importance. Firstly, the method used for fitting the lag requires that parameters be imposed on the data rather than endogenously determined. Secondly, two variables are inappropriately deflated. The TFP index is constructed as a price-weighted value of output series, appropriately deflated, divided by a price weighted value of inputs series, that was not deflated by the appropriate price index. The inputs included labour, land and capital services, whereas the price index used for deflating to get a volume of inputs (Goods and Services Currently Consumed) does not cover these items. Similarly, the R & D expenditures were converted to a physical volume of R & D inputs by deflating with the RPI, when the appropriate deflator would be an R & D deflator based on the wages and salaries of scientific personnel and the price of other R & D inputs.

Thirdly there are two conceptual difficulties. Public and private R & D are treated symetrically, when in fact their effects are usually expected to be different. Griliches (1964), for example, assumed that the private sector input companies would succeed in embodying new technology in their products and raise their prices sufficiently to appropriate all the returns to their R & D.[25] These price increases should be reflected as quality change in properly quality-adjusted input series and these would not show up in a residual measure of technical change in agriculture.[26] Public sector research output must be accounted for separately, by including expenditures, as an input in the production function, exactly because the returns are mostly not appropriated by the institutions and hence not charged for in the normal way. Hence, private sector research need be taken into account only to the extent that the data lacks quality adjustment. Doyle and Ridout's (1985) doubling of public R & D expenditures to allow for the private effort would be appropriate only if there were no appropriability of private returns and/or no quality adjustment in the input series (Thirtle, 1986).

Lastly, the treatment of the R & D variable, or knowledge capital stock is unconventional in that it is deliberately constructed so as to stay constant rather than fall if there is no R & D expenditure. This is at odds with the usual reasoning (Bonnen, 1983), which suggests that the agricultural technology stock depreciates in the absence of maintenance expenditures.

These difficulties combine to produce a Durbin-Watson statistic of 0.74, indicating that the error structure is autocorrelated. The suspicion has to be that the systematic elements in the error structure result from mis-specification in the form of omitted variables and errors in variables. Hendry (1980) has addressed the well known fact that when one variable with a strong time trend is regressed on another similar entity, large $R^2$'s and significant coefficients may mean very little. A poor Durbin-Watson statistic is likely to be evidence of the spurious nature of the relationship.

## VIII. EVALUATION

Although the current study appears to have overcome some of these fairly obvious pitfalls, and there is no evidence of serial correlation, the basic cause for doubting the results remains. The quality of data for both the dependent and independent variables is dubious, and both have strong upward trends.

Figure I, below shows a comparison of the first difference of three of the TFP indices. The large discrepancies prior to 1975 suggest that if the trend is removed, not much is left.

Table V shows how low the level of agreement is, with correlation coefficients for the first differences of the TFP series as low as 0.5. The solution here is clearly more and better data. This matter is now work in process (Bottomley, Ozanne & Thirtle 1988).

The choice of index type (arithmetic, Tornqvist, etc.) is only a minor source of variation as Diewert (1978) has shown. But the treatment of quality change, especially for the land and capital inputs, leads to large disparities[27] as does the method of conversion of capital from a stock to a flow.

Recently econometricians have increased interest in sensitivity analysis (Leamer 1983, 1985, McAleer et.al. 1985, McClosky 1985, 1986) and the problem of testing model specification. Here lack of data prevents attempts to do much in the way of alternative specification, but experimentation with all the series available shows the estimates to be surprisingly robust. We continue this process by considering model error. Whereas we have fitted the "conventional" model of equation (7), which is well supported in the literature, the distributed lag could be modelled differently.

The limitations of the data's ability to discriminate between models which

# U.K. AGRICULTURAL PRODUCTIVITY INDICES:

FIRST DIFFERENCES

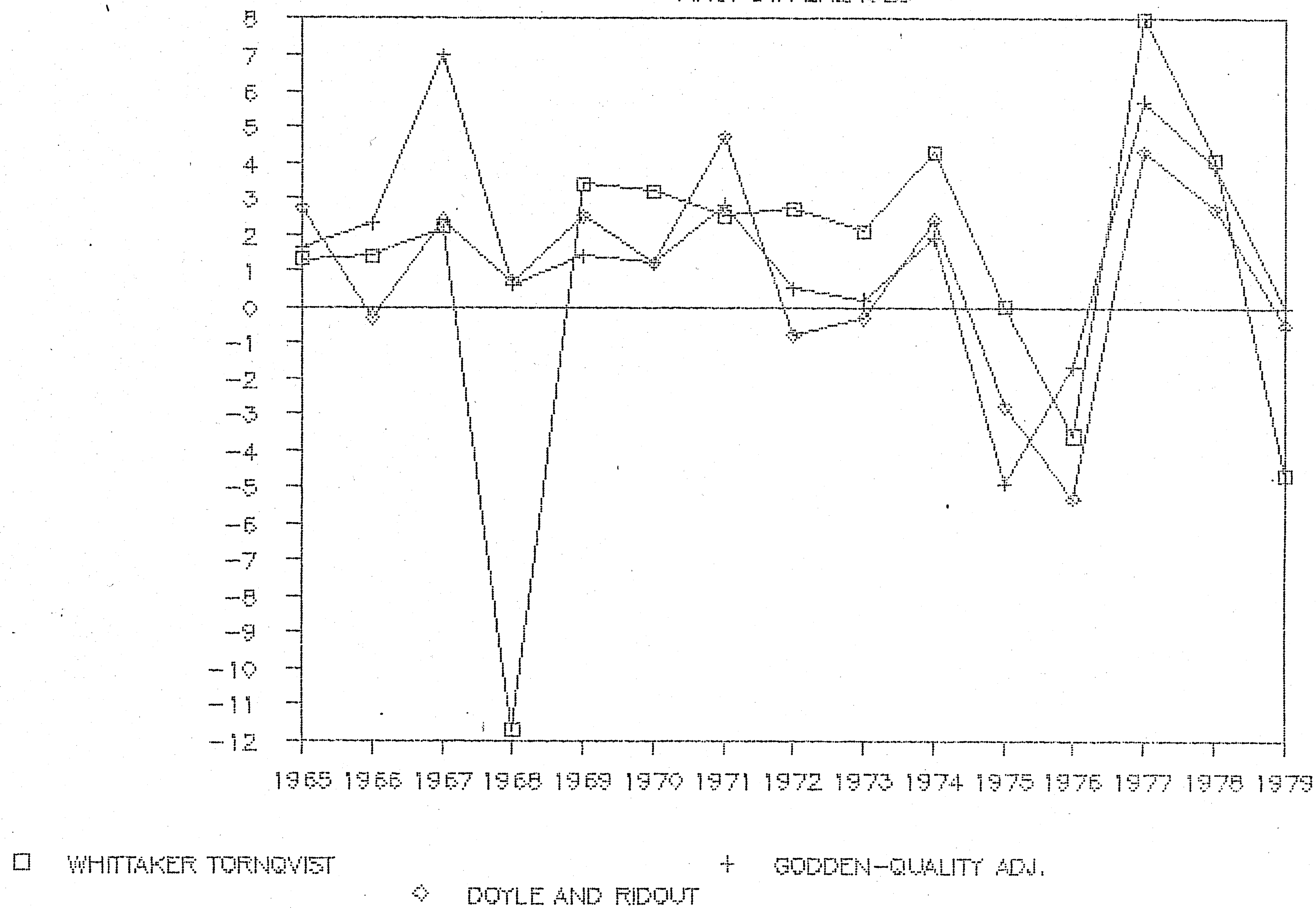

Table V : Comparison of Total Factor Productivity Indices: Correlation Coefficients of First Differences

| | Whittaker Laspeyres | Whittaker Tornqvist | Godden, Q Adjusted | Godden Unadjusted | Doyle and Ridout |
|---|---|---|---|---|---|
| Whittaker Laspeyres | - | 0.757 | 0.848 | 0.850 | 0.826 |
| Whittaker Tornqvist | - | - | 0.505 | 0.512 | 0.445 |
| Godden Q Adjusted | - | - | - | 1.00 | .776 |
| Godden Unadjusted | - | - | - | - | .763 |
| Doyle and Ridout | - | - | - | - | - |

was suggested in Section V can be illustrated by fitting a lag structure that is quite at odds with theoretical notions on the structure of returns to R & D. Applying Koyck's (1954) transformation, to equation (7) (with education omitted), gives;

$$(14) \quad \ln P_t = a_0(1-\theta) + \theta \ln P_{t-1} + \alpha_1 \ln R_t + B_2 \ln W_t - B_2 \theta \ln W_{t-1} + u_t - \theta u_{t-1}$$

This equation imposes geometrically declining weights to R & D over time and is hence entirely at odds with the reasoning behind the conventional model, but fits as well, if not better. All the estimated coefficients were positive and significant (except for lagged weather), the adjusted $R^2$ was 0.97 and the Durbin Watson was 1.9014. Because the largest returns to R & D fall in the early periods, the MIRR rises to 260%![28]

The econometric difficulties discussed above are the main impediments to economic analysis of agricultural R & D. The difficulties involved in calculating the MIRR are secondary problems but have attracted a lot of attention. However, since small changes in productivity translate into large changes in the value of output ($\Delta Y_t/\Delta P_t$ in equation (12), minor errors in the TFP index cause large errors in MIRR calculations. Wise (1981, 1984) has belaboured the issue of errors of approximation in the cost benefit approach, where economists are guilty of using linear approximations of non-linear functions. In his (1986) critique of the production function approach, he takes pains to show that the approximations used by Griliches (1964) and Peterson (1967) over-estimate the rate of return. Perhaps this is why more sophisticated techniques are now used? Even so, most practitioners would agree with Davis (1981), that a set of conventions for research project appraisal would help.

Apart from these technical problems, there are serious conceptual difficulties. Firstly, in the present study, output was evaluated at U.K. prices, which under the Common Agricultural Policy (CAP) are anything between 50% and 100% higher than world prices.[29] If the consumer's evaluation based on distorted market prices is accepted then no adjustment is needed, but if the opportunity cost of agricultural output is taken to be a more reasonable measure of value, the estimated rate of return calculated above would fall appreciably. But there is a powerful argument for not adjusting prices downwards at all. It is well established that in a competitive industry facing an inelastic demand, technological change shifts the supply curve to the right, continually reducing prices and passing the benefits on to consumers.[30] Hence, the price used in the evaluation of output are reduced by technical change, giving an argument in favour of an upward adjustment.[31]

Other failings of this piece of work appear to be entirely general. For example, no account is taken of external effects. One reason is surely that it is not clear that most diseconomies in agriculture can be attributed to technological change. Intensification, resulting from the CAP price policy is the main cause of pollution and loss of rural amenity and even the spread of vile-smelling rapeseed (but what a pretty colour?).

Another adjustment factor that would seriously reduce the MIRR has been pointed out by Fox (1985). The marginal cost of a Pound of public sector research funding may be as high as £1.30, due to the deadweight loss associated with tax collection.

Spillovers of new technology from one jurisdiction to others is an even more insoluable problem. The smaller the economy, the greater the difficulty, since externalities may outweight direct effects. To use oilseed rape as the example, again, British plant breeding efforts have failed, but the Dutch, French and German new varieties are doing so well that ADAS trials on disease control, post harvest technology etc. appear to show a benefit/cost ratio of 325 (Russell & Thirtle, 1988).

The empirical problems have been mentioned in passing, but are formidable when gathered together.[32] Constructing TFP indices raises insoluable quality adjustment and other measurement difficulties. Equilibrium is assumed to hold throughout, which can't be true in agriculture. Separability is requied between outputs, conventional inputs and non-conventional inputs. Worse still, the Cobb Douglas has dominated this area and requires that each input be its own separable group, which makes no sense when R & D, extension and education are too closely complimentary to be separated (Bonnen 1983). Clearly, testing is required to establish separability and if it does not hold the functional form must be changed and "integrated" estimation (Evenson, et.al. 1987) must replace the present two-stage approach. Causality tests are also required and have been undertaken (Pardey & Craig 1988). The shape, length and lead time (if any) of the lag structure should be endogenously determined. Finally, the problem of omitted variables cannot be overlooked, when private R & D expenditures, which now exceed public spending, are included in this category. This catalogue of heresies and errors may not matter if the object of attention were a major share of agricultural output, but given it is about 2% of the total, the size of the confidence interval on any estimate of the returns to R & D must be enormous.

## IX. CONCLUSIONS

The crude MIRR of 100% calculated in section VI must be adjusted considerably, when allowance is made for negative agricultural externalities, policy induced price distortions and the marginal cost of public funds. Even so, the final figure would be in excess of 50%, though this study suggests that the estimate is very rough and should have a large confidence interval.

Further progress with econometric investigations can improve the accuracy of estimates in this area, but it may still be necessary to follow the lead of Nelson (1982) and ACARD (1986) and revert to the case study approach. Some form of objective inquiry should provide the information necessary for decision making in research resource allocation. If there is none, cuts are likely to continue with no better basis than the political expediency and the spectre of ever increasing agricultural surpluses, exacerbated by technical change. Cutting agricultural research budgets may be easier than reforming the CAP, but the lakes and mountains will continue to grow. They will just be produced less efficiently.

Footnotes

1. This is not to say that farmers don't contribute to technical change in agriculture. Evenson (in Nelson, 1982, p.237) estimates that American farmers devote as much as a quarter of their time to screening of new technologies. Also, the importance of timing and the scope for combining the same inputs in different ways leaves plenty of room for informal research and farm-level innovations.

2. Hence the recent emphasis applied on identifying "exploitable areas of science" (Advisory Council for Applied Research and Development, 1986). Agriculture seems to have been identified as the ultimate unexploitable area.

3. There are occasional dissenters such as Pasour and Johnson (1982), but see also Ruttan's (1982) reply, which defends the conventional wisdom and also Oehmke, (1986) who explains why underinvestment persists in this area.

4. Argued by Schuh (1986), in his appraisal of Ruttan's contribution, for which Ruttan became the first economist to receive the von Humboldt award, for services to American agriculture.

5. For example, Grossfield and Heath (1966) and Lund, Irving and Chapman (1980) who point out that resources must be allocated on the basis of <u>ex-ante</u> evaluations of costs and benefits.

6. See Griliches (1985) on the difficulties that arise when the data collectors and the data users are not the same people.

7. Thus, for example the Tornqvist-Theil discrete approximation of the continuous Divisia index is exact for the translog production function. The arithmetic index is exact for the linear production function, etc.

8. See Berndt and Christensen (1973). Given that the data were assembled for other reasons, it is unlikely that the grouping used for aggregation will be appropriate for economic studies.

9. This amounts to aggregating until there is only one output and only one conventional input (composed of all the traditional factors). The total factor productivity index is based on the ratio of these two aggregates. This requires that outputs, conventional inputs and non-conventional inputs should form separable groups.

10. The choice of functional form for the index is a minor cause of measurement error relative to the difficulties involved in handling quality change. The Divisia index is exact for the translog function and is less restrictive than the geometric index that is exact for the Cobb Douglas.

11. For example, in plant breeding, yield gains tend to be lost over time if research on a variety is not maintained, since the pests and diseases evolve, making the variety susceptible to attack when it was initially immune. Hence maintenance expenditures tend to be required to prevent falling productivity. This issue has been investigated by Blakeslee (1987).

12. See Lu, Cline and Quance (1979, p.15) for a description of the stages involved in research and diffusion. This section follows their approach, which is typical of the U.S. literature.

13. Kindly provided by Harvey Beck of the Economics Panel for Agricultural Research and Development, University of Reading.

14. Thanks to C. Pissarides, who made these data available to us.

15. Data may be available from internal sources or can perhaps be extracted from the R & D series reported in Parliamentary Papers, though there are considerable difficulties.

16. Doyle and Ridout's index extends to 1981. Whittaker's to 1979 and Godden's to 1980.

17. The Cobb Douglas form used here should be rejected on theoretical grounds. For instance, it assumes that the inputs are functionally separable, when in fact they are extremely interdependent. However, preliminary investigation suggests that the data are too poor to support a functional form that is less parsimonious in parameters. Choice of functional form is is this case relegated to an issue of secondary importance, as more obvious sources of error become apparent. For example, equation (6) is estimated with the end-points of the lag constrained to equal zero at period t-i = (0-1) and t-i = (n+1), so that the returns begin in year zero and continue until year n. Endogenous determination would clearly be preferable, but the data would not support it.

18. The correlation coefficient for education and Doyle and Ridout's R & D index was 0.83.

19. This section is based on Lu, Cline and Quance (1979) and Davis (1981).

20. These data are from the Ministry of Agriculture, Fisheries and Food (MAFF). (various issues). Both output values and R & D expenditure should be converted to constant Pounds using a consumer price index. Particularly, go the R & D expenditures used in the MIRR calculations should be deflated with a consumer price index, not the scientific manpower deflator used in the regression analysis (Davis (1981)).

21. Davis (1980) shows that the choice of lag structure has little effect on the VMP calculations but he has argued elsewhere (Davis 1981) that alternative MIRR calculations do cause large variations. However, the pioneering results of Griliches and others are clearly gross approximations and should not be allowed to give the impression that there are measurement problems. These old results are used in this way by Wise (1986).

22. These figures are all from MAFF (1986).

23. This calculation does not allow for the lag between expenditures and returns. More realistically, a simple estimate can be made by assuming that the 1985 return resulted from expenditures occurring say seven years earlier. Discounting the return of £220 million at 5% for seven years and dividing the result by the 1978 expenditure of £115.7 million gives a return on capital of 35%.

24. This obviously catches the weather and all other causes of the variance in output. Thus, if their TFP index were for cereals alone they would have an $R^2$ of very close to unity. Indeed, it could be argued that their weather variable is an ideal instrument.

25. Strictly speaking, this requires the input supplies to be monopolists. If they are not, only the cost. rather than the return, will be reflected in the input price series (Griliches, 1979).

26. Indeed, Kislev and Peterson (1982) have argued that there is no technical change in agriculture. All the progress should be attributable to the agricultural input industries.

27. See Griliches' (1960) comparisons of the United States Department of Agriculture and the Bureau of Labour Statistics farm machinery and equipment statistics and Thirtle (1986).

28. Following Hendry (1980) the R & D series was also replaced by cumulative rainfall. The coefficient on the dependent variable was positive and significant and the adjusted $R^2$ rose to 0.89. However this entirely spurious model did generate a Durbin Watson statistic of 0.31, which does suggest that this statistic can be a good indicator.

29. In addition, costs of storage of agricultural surpluses are approximately equal to public sector R & D expenditure.

30. The other main claimants to income streams generated by technical change are the owners of factors that are least elastic in supply. All the evidence suggests that landlords gain disproportionately high gains from new agricultural technology. Where simple price weights are used to aggregate inputs, the TFP index will not reflect these gains either.

31. The complex issues of how to deal with policy induced distortions has attracted considerable recent attention (Norton, Ganoza and Pomareda (1987), Alston, Edwards and Freebairn (1988), and Oehmke (1988)) but this literature provides no easy answers for a case like this.

32. It should be added that the model does not work at all in first differences.

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