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Problems in the Definition and Measurement of Technical Change and Productivity Growth in the U.K. Agricultural Sector

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(WP/03)

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(1) Conceptual Issues and Problems

For individual agricultural research projects with a well defined output, social cost benefit analysis may provide a means of evaluating the contribution of new technology to agricultural production.[1] Alternatively, it may be preferable to measure the flow of inventive output or the stock of technical knowledge rather than concentrating on individual elements. This is the approach considered in this paper.

(a) Direct Measurement of New Technology

Several variables have been used in attempts to measure directly the output of invention or innovation. In agricultural economics, Evenson (1982) used patent data to investigate mechanical technological change[2] in the USA and Binswanger (1984) has extended the analysis to other countries. Certification data for new seed varieties could be used in a similar manner to consider biological technical change. Mensch (1979) counted the number of significant innovations[3] emanating from particular industries, which may more closely reflect economic importance than does patenting. License information has been similarly employed in the measurement of international technology flows. "Scientific output" has been quantified by Evenson and Kislev (1975) by enumeration of scientific journal articles.[4] A further important source of information, largely peculiar to agriculture, is the trial records kept by research establishments. For example, Godden (1985) used NIAB trial plot data to estimate the contribution of new cereal varieties to U.K. cereal yields.

(b) Output Effects of Technical Change

The difficulties involved in measuring technological change directly are sufficiently formidable to have led economists to measure instead its effects on output. Any such measure of technical change reflects the average practice technique of the industry, so that we have to consider the usual sequence of invention, innovation and diffusion.[5] Output measures of technical chage rest on definitions such as "the production of a greater output with a given quantity of resources" (Peterson and Hayami, 1977), corresponding to an upward shift of the production function. Kuznets (1978) argues that "output based" measures of technical change suffer from at least three shortcomings. Firstly "a cost-reducing innovation has a different effect in an industry with a product of low long-term income and price elasticity of demand from that in a sector producing goods of high demand elasticity" (p. 335). Secondly, to count the proportion of the product attributable to new components will give a gross value whereas the real contribution is net of the costs involved in obsolescence and the dislocation caused by disturbing old ways. Thirdly, an output measure will be partial, failing to take account of the fact that important technical changes lead to organisational and social changes that may be far-reaching. "It follows that the net economic yield of a given technological innovation (or a group of them) must involve not only a comparison of the economic value of output and input as conventionally measured, but also an evaluation of the required changes in conditions of work and life, of both the complementary and dislocative adjustments.....; the difficulties are enormous." (Kuznets, 1978, p. 342).

(2) Technical Issues and Problems

(a) Technical Change and Total Factor Productivity

Although it is not hard to find claims that productivity growth and technical change are synonymous (Dogramaci, 1983, p.2, for example), most authors argue that new technology is the most important determinant of productivity growth, but not the only one. Solow and Temin (1985, p. 93) note that the other major causes of productivity growth are increasing returns to scale and improved efficiency in the allocation of resources. The second of these includes both structural change (not relevant at the one-industry level) and specialisation and the division of labour (a very long run proposition).

Thus, for UK agriculture, the main causes of total factor productivity growth could be thought of as technical change and increasing returns. The new technology will generally be embodied in capital equipment thus requiring investment and will be associated with investments in human capital. However, Mathias (1983, p.18) argues that this economist's perception is far too narrow. "Gains in productivity do not come alone from the installation of new technology - but involve also the commitment of workers, the efficiencies of management and organisation, the provision of specialist financial and business professional services, the financing, distribution, selling and market orientation of products."

A further complication is that what is actually included in total factor productivity will depend on the procedure followed. In growth accounting exercises, this may (deliberately) include factors such as the changing composition of the labour force, education and learning-by-doing.[6] The role of these items will depend on the approach taken to quality adjustment, discussed in (e), below.

(b) Technical Change and Factor Substitution

If we do settle for measures of technical change based on changes in input and output levels, a range of technical problems remain. Even in Solow's (1957) two-factor model of growth there is a clear problem of differentiating between movements along the production function (factor substitution) and an upward shift of the function (technical change). The relative shares of the two concepts in explaining any given change depend on the definition of the neoclassical isoquant, a construct that has been attacked by Rosenberg (1976) and Nelson (1980).

Hayami and Ruttan (1971) resolve the problem by arguing that in the very long run ("secular period") "technology can be so developed as to facilitate the substitution of relatively abundant (hence cheap) factors for relatively scarce (hence expensive) factors in the economy". In DC agriculture, chemicals and improved seed varieties have been substituted for land (biological/ chemical technical change) and power, machinery and equipment has been substituted for labour (mechanical technical change). Thirtle (1985b) shows that for U.S. field crops, from 1939-78, increases in fertilizer per acre are of an order of magnitude that can be explained by normal values of the elasticity of substitution but the rate of increase of machinery per unit of labour is too large to explain in this way. Both Hayami and Ruttan (1985, Ch. 7) and Thirtle (1985a) establish the importance of technical change relative to factor substitution (subject to neoclassical definitions of these terms). However, there are extremely large variations in the estimated values of substitution elasticities. See for example Binswanger's (1978) results for U.S. agriculture (derived from cross-section data)[7] as compared with Ray (1982) whose sample is time series, or Brown and Christensen (1981).

(c) Technical Change and Increasing Returns to Scale

The introduction of new technology may lead directly to scale economies, making the two notions difficult to separate, both conceptually and empirically (Peterson and Hayami, 1977, p. 505). The paper by Zanias (1985), reported below, clearly has this problem, since with time series data for aggregate U.K. agricultural output it is not possible to discriminate between "quasi increasing returns"[8] and technical change. Dogramaci (1983) briefly reviews attempts to solve this problem, beginning with the original controversy between Stigler and Solow, down to Sato's (1981) solution based on the application of Lie groups.

(d) Product and Process Innovations

Process innovation may be described as new ways of making old things, while product innovation means old ways of producing new goods (Blaug, 1963). This distinction, like many others in economics, does not hold up too well.

In agriculture much new technology is produced by the private sector farm input industries, especially the farm machinery and equipment and agricultural chemical industries. Process innovations in these industries should simply lower the costs of their outputs, reducing the input costs of the agricultural sector itself. Product innovations in these industries should ideally be captured by quality-adjustment of the series for agricultural inputs. If the companies concerned succeed in appropriating the full benefits of their inventive activity, then this price-based quality adjustment would correctly attribute all product innovation in the intermediate input industries to the non-agricultural sector.[9] (Griliches, 1973). Less than full appropriability will result in part of the benefit being recorded as process innovation in the agricultural sector.

(e) Embodied and Disembodied Technical Change

The conception of technical change as disembodied "manna from heaven", not connected with any factors of production, has provided a convenient straw man for those who have argued that "technical change" is nothing but measurement error.[10]

"It is important to recognise that in order to have changes in output per unit of input or to have shifts in a production function there must be changes in the quality of the inputs. The fact that we observe productivity changes means that some inputs have changed in quality and these quality changes are not reflected in the total input measure..... If a unit of input is defined in terms of its contribution to production, the total output must move in direct proportion to total input.[11] It is just an accounting identity" (Peterson and Hayami, 1977, p. 498).

This statement of the Jorgenson and Griliches (1967) view is sufficiently disingenious to be obviously too simplistic. Though "learning by doing" properly applies to capital goods industries and would hence be captured in the lower cost of agricultural intermediate inputs, a similar process which

Rosenberg (1982) calls "learning by using" must occur on farm. The new technology that results may either be disembodied or may require embodiment by way of say, the redesigning of a piece of equipment. This requires a feedback loop allowing difficulties in use to be overcome by design changes. Biggs and Clay (1981) have argued that "informal", on-farm agricultural research should not be ignored. Much of its output may be disembodied, in the sense that it may not have entered the process embodied in an input. For instance agricultural production allows considerable scope for finding new uses for inputs, combining them in novel ways and particularly the timing of operations can be crucial. Rogers (1983) has coined the term "re-invention"; his discussion of the concept begins with an agricultural example.

To summarise, approaches to the "quality adjustment problem" range from the "measure of physical volume" or no-quality-change approach at one end of the spectrum to the explain-everything, measurement in "efficiency units" approach that insists that inputs add up to output. (The terms are from Tolley, 1961). In the study of agricultural production, the basic issue is illustrated by the treatment of non-conventional inputs. For example, Griliches (1963) showed that education could either be included separately or used to quality-adjust the labour input series. If all inputs are included, then they will fully explain output but some, like "learning by using" on the farm cannot be captured in official statistics. Hence, even fully quality-adjusted input series will not completely explain output, but this does not necessarily result in residual, disembodied technological change, since many functional forms used to estimate production functions allow endogenous factor-specific estimation of "embodied" technical change.

Kendrick and Vaccara (1980, p. 5) correctly suggest that, "in the last analysis, it is perhaps not so important whether input quality changes are counted as part of changes in the quality of inputs or as part of the explanation of productivity change, so long as the variables are identified and their separate contributions to growth are quantified. The differences in accounting schemes can then be reconciled."

(f) Public Sector Research and Development

The arguments above are complicated by the contribution of the public sector, especially in new varieties of field crops. Ruttan (1982, p. 199) argues that even in countries that have attempted to strengthen private incentives through plant variety protection legislation, appropriability is still low and hence the public sector contribution is crucial. Evenson (1982, p. 274) suggests that a natural division of labour has emerged (in the U.S.) with the public sector producing plant breeding material while the private sector develops the final product. Thus the output of the public sector is acquired at well below cost by input suppliers such as seed companies, and incorporated in their product. Quality changes resulting from public sector research output cannot be expected to be captured in price-weighted quality adjusted input series. This led Griliches (1964) to include public research and extension expenditures[12] as an explanatory variable in the production function.

(3) Measurement Problems

(a) Choice of Index

Tolley (1961) recommended a neoclassical approach to productivity indices, suggesting that the objective should be to measure shifts in the production function. The production theory approach has been used by the USDA (1980) to explain the commonly used (Laspeyres) arithmetic index which corresponds to a linear production relationship and hence imposes elasticities of factor substitution of zero. Solow's (1957) geometric index, the main alternative, corresponds to a Cobb Douglas function and imposes unitary substitution elasticities.[13] Whittaker (1983) shows that both may be viewed as approximating the production function with a first order Taylor's series expansion (i.e. the tangent to the curve). A second order expansion would provide a far better approximation; but the second derivative of the function is not observable. Other indices, corresponding to simple functions such as the CES (favoured by Brown, 1966) suffer from the same problem of imposing arbitrary parameter values. In all cases the measures are affected by the choice of base period for the weights.

However, the realisation that index number formulae can be derived explicitly from particular production functions has provided a powerful new basis for selecting index procedures (Caves, Christensen and Diewert, 1982). A production function with suitable properties can be selected and the corresponding "exact" index derived. Diewert (1976) argues in favour of flexible functional forms (that can provide a second order approximation of an arbitrary production function), calling index numbers that are exact for such functions "superlative".

The most popular superlative index has proved to be the Tornqvist-Theil approximation of the Divisia index[14] which is exact for the translog production function. Diewert (1978) has also shown that if a quantity index is superlative, the implicit price index defined by Fisher's (1922) weak factor reversal test, will also be superlative. Allen and Diewert (1981) consider the choice between direct and implicit index number formulae.[15]

A set of Tornqvist-Theil input and output indices for U.S. agriculture have been constructed by Ball (1985) who uses them to estimate total factor productivity. The result shows that the USDA Laspeyres arithmetic index of total factor productivity fares rather well, for all the criticisms that have been levelled at it (Griliches, 1960 is the most famous).

(b) Aggregation and Quality Change

Desai (1976) considers separately aggregation, measurement and index number problems before pointing out that in reality they are inextricably interwoven. Berndt and Christensen's (1973) investigation of the relationship between substitution, aggregation and separability has clarified the issues,[16] but Blackorby and Schworm (1984) argue that the technologies of firms are very unlikely to be consistent with capital aggregation.

In practice, aggregation is inevitable and Star (1974) has pointed out that quality change problems are simply another name for errors in aggregation, that occur because there are changes in the components of the mix making up the aggregate (Christensen 1975). Ball's (1985) treatment of the labour input shows how this difficulty can be largely dealt with by a superlative index procedure. Frequent changes in price-weights applied to a labour data matrix decomposed into two sexes, eight age groups, five educational groups, two employment classes and ten occupational groups, results in a very fair effort at including quality change.[17] Unfortunately, the data, developed by Gollup and Jorgenson (1980), are available only for labour.

(c) Treatment of Other Inputs and Output

(i) Fertilizer

Since the nutrient content of a ton of fertilizer has not remained constant, quality adjustment of the input series is required. Hayami and Ruttan (1971) resorted to an unweighted average of the three main nutrients. Griliches (1960) recommended a price-weighted average of N, P and K. Rayner and Lingard (1971) tackled the further problem that if the associated price series is required, a "price of nutrients" series must be generated.

(ii) Other Agricultural Chemicals

These cannot be handled so simply. If the series is a price-weighted composite of several hetrogeneous inputs, then it must be deflated by a hedonic price index that is appropriately adjusted to allow for quality change.

(iii) Machinery and Other Capital Items

Crude "quality adjustment" approaches include Hayami and Ruttan's (1971) resort to tractor horsepower, but such a measure obviously excludes other equipment. Again, if a value series is to be used it should be deflated by a quality adjusted price series such as the tractor price series developed by Fettig (1963) or Rayner (1966). Kislev and Peterson (1981) have used a price series for custom rates for harvesting, to generate a machinery series that increases very much faster than the USDA series.[18] Capital items also raise the stock-flow problem since it is the actual input of factor services that we would like to include. The issue is discussed in USDA (1980).

(iv) Land

Land can be quality adjusted for improvements in the manner attempted by Godden (1985) for the UK case. He includes a series for "improvements" (see Table II). Again, the concept of a service flow of farm real estate is an attractive input concept. The USDA (1980) uses interest on land and farm buildings, depreciation and damage to buildings plus repair costs to buildings and grazing fees, to approximate the service flow.

(v) Seeds

Where the contribution of new varieties has been independently estimated (Godden, 1985) this exogenous information could be used in productivity calculations. This would seem useful since the neoclassical "factor price equal to marginal revenue product" assumption, which is crucial to the input index calculation would seem to be especially far fetched in the case of seeds. Firstly, the new technology tends to be a "public good" and the returns may not have been appropriated and secondly, seed ratios are pretty much fixed. An increase in marginal value product will not be diminished by heavier application (as could occur with say fertilizer).

(vi) Non-conventional Inputs

Excluding any inputs will clearly cause a residual measure of "technical change". The USDA (1980) discusses the appropriate treatment of irrigation water, "environmental inputs", public infrastructure, insurance and government activity, (as well as research and extension).

(vii) Output

The measurement of output raises a further problem, in that gross output (but some measures are more gross than others) or value added may be more appropriate. Disaggregated estimates of technical change for different sub-sectors such as crops, livestock and horticulture would also help in the evaluation of the productivity of research. Generally these estimates are made difficult by the lack of data on the allocation of certain inputs such as labour, machinery and fertiizer. However, Just, Zilberman and Hochman (1983) provide a methodology for endogenous estimation of the unobserved input allocations.

(4) Empirical Results for the UK

Though there has been very considerable progress in the area of productivity measurement, any illusion that agreement has been reached or that unambiguous answers are possible can be dispelled by consulting the literature. Norsworthy (1984) performs the useful service of comparing the approaches and results of the three most persistent practitioners; Denison, Jorgenson and Kendrick. Norsworthy and Malmquist (1983) examine the effects of different assumptions on issues such as neutrality of technical change and separability.

Whereas a wide range of production, cost, or profit function studies are available for some countries (these are listed in Thirtle and Ruttan, forthcoming) the UK evidence is limited. Wade (1973) provides estimates of neutral land and labour-saving technical changes derived from fitting a two input CES to land and labour data for UK agriculture up to 1960. Zanais (1985) finds 1.3% Hicks neutral technical change for UK agriculture for 1949-83. This figure should be viewed as a lower bound, since his model cannot discriminate between technical change and increasing returns to scale and the sum of his output elasticities is 1.332. Godden (1985, pp.234-7) provides estimates of factor-specific technical changes using equations derived from a general linear variable profit function. He found technical change to be materials-using, but failed to produce an estimate for labour, which was the other variable input. For the fixed inputs, his results show that technical change increased the price of land and improvements but made plant cheaper.

Godden's considerable effort well demonstrates the difficulties involved in the estimation of production relationships. The calculation of total factor productivity indices is a less ambitious undertaking. Whereas productional analysis aims to estimate income distribution, returns to scale, elasticities of factor substitution, separability and technical change (Fuss and McFadden, 1978, pp. 220-21) a productivity index will provide more limited information. Unlike a model, it will generate no test statistics or estimated coefficients that must comply with theory. Even so both Caves, Christensen and Diewart (1982) and Berndt (1978, p. 258) show that if the assumption of constant returns to scale is unobjectionable, then the Tornqvist index will provide an approximation of the effect of "technical change".[19]

Table I compares total factor productivity estimates by MAFF (1969), Whittaker (1983), Godden (1985) and Doyle and Ridout (1985).[20] Note that the indices referred to as "Tornqvist" are Tornqvist aggregates of (Laspeyres) arithmetic indices supplied by MAFF. Table II, from Godden (1985) shows annual rates of technical change, by decade, according to level of aggregation.

(5) Conclusion

The total factor productivity indices listed in Table I are an obvious first step, in the quantification of UK agricultural productivity. Unfortunately, the level of agreement is not high. As Table III shows, the correlation coefficients between the five series that extend from 1965-79 varies considerably. Whittaker's Tornqvist index is quite unlike the other series, with correlation coefficients of around 0.5 (row two). Her Laspeyres index, Godden's efforts and Doyle and Ridout's index are fairly similar, with coefficients between 0.82 and 0.85 (row one). Godden's series and Doyle and Ridout are less alike, with coefficients of 0.76.[21] The plots of the indices given in Figure I show that the series tend to be very similar for the last five years, reasonably close for the middle period and quite dissimilar for the first five years of the period.

Godden (1985) has tried to go considerably further, but his full production analysis, tends to show why the productivity indices should not be taken too seriously. His main problems appear to be (a) data of poor quality, (b) inappropriate aggregation, (c) the "technology treadmill" results in falling prices being collinear with rising output, which tends to produce parameter values that suggest downward sloping supply curves,[22] (d) plain bad luck adds to (c) in that the big vaccilation in his series - the jump in prices associated with joining the EEC is also accompanied by falling output due to bad weather.

With extreme care and good fortune, production function estimation[23] may produce sensible results, but Godden's work raises doubts as to the adequacy of U.K. aggregate agricultural data for supporting studies of this type.

Table I : Comparative Estimates of Rates of Hicks-neutral Disembodied Technological Change in Aggregate U.K. Agriculture (% p.a.)

	MAFF	Whittaker		Godden		Doyle and Ridout
		Laspeyre's	Tornqvist	Quality adjusted investment	Non-quality adjusted investment	
1965	1.6	0.9	1.3	2.7	2.8	1.6
1966	1.1	0.9	1.4	-0.3	-0.2	2.3
1967	3.4	3.4	2.2	2.4	2.5	7.0
1968	-1.7	-2.4	-11.7	0.7	0.8	0.6
1969	2.7	2.8	3.4	2.5	2.6	1.4
1970	2.1	3.3	3.2	1.2	1.4	1.2
1971	3.1	3.7	2.6	4.7	4.9	2.8
1972	0.0	0.8	2.7	-0.8	-0.7	0.5
1973	1.0	2.3	2.0	-0.3	-0.1	0.2
1974		2.2	4.1	2.4	2.7	1.9
1975		-4.7	0.0	-2.8	-2.6	-4.9
1976		-4.1	-3.3	-5.4	-5.2	-1.7
1977		6.9	7.6	5.3	5.6	5.7
1978		3.4	3.6	2.7	2.9	3.9
1979		-2.2	-3.0	-0.5	-0.3	0.0
1980		-	-	6.5	6.7	4.2
1981		-	-	-	-	0.0

Sources: Columns 1 and 2, Whittaker (1983, p.77); Column 3, Whittaker (1983, p.89); reproduced with the kind permission of the author. The 1975 value in the second column has had a minus sign inserted that was omitted in the source.

Column 4, estimated using data described in Godden, Chapter 5, by growth equations method with a four output Tornqvist index and a nine input Tornqvist index.

Column 5, as for column 4 except that investment in improvements and plant not adjusted for estimated quality changes.

Column 6, Doyle and Ridout (1985, p. 110).
(Taken from Godden, 1985, p.225).

Note: There are minor differences between these figures presented by Godden and those in Whittaker (1983).

Table II : Growth Equation Estimates of Hicks-neutral Disembodied Technological Change in Aggregate U.K. Agriculture (average % p.a.)

	Decades				Pre- and post-EC entry		
	1950-60	1960-70	1970-80	1971-80[a]	1964-72	1973-80	1983-80[a]
(i) nine inputs[b]							
- arithmetic[e]	2.77	2.01	1.09	2.04	1.68	0.79	1.92
- Tornqvist[f]	2.86	2.01	1.11	2.07	1.62	0.92	2.13
(ii) five inputs[c]							
- arithmetic[e]	2.81	1.99	1.12	2.08	1.69	0.81	1.95
- Tornqvist[f]	2.90	1.99	1.14	2.11	1.63	0.94	2.17
(iii) three inputs[d]							
- arithmetic[e]	2.83	2.00	1.15	2.11	1.69	0.84	1.99
- Tornqvist[f]	2.91	2.00	1.17	2.14	1.64	0.97	2.21
(iv) non-quality adjusted investment[b,f]							
	2.84	2.09	1.33	2.28	1.74	1.15	2.36

Notes:

a. excluding drought years 1975-76 and recovery year 1977 (estimated by geometric mean of rates of change in other years)

b. labour, feed, seed, fertilizer, fuel and repairs, miscellaneous materials, land, improvements, plant

c. labour, materials, land, improvements, plant

d. labour, materials, aggregate capital

e. arithmetic output index: Y = value/price index; Tornqvist input

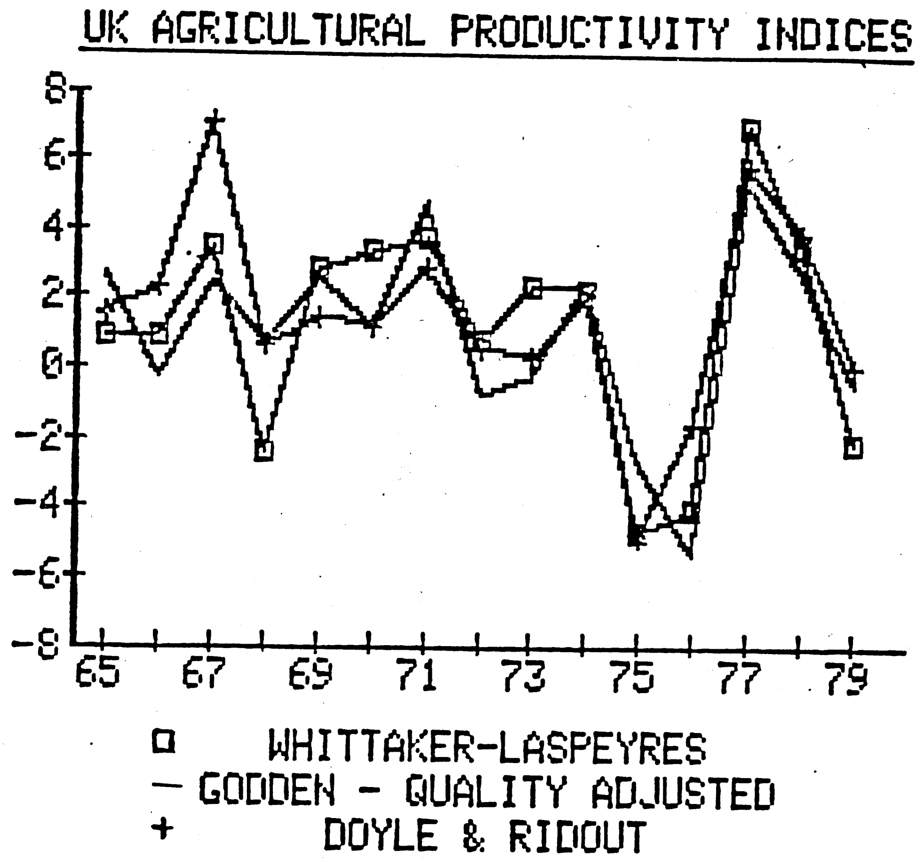
f. Tornqvist output index: $Y_{01} = \prod_i (y_{i1}/y_{i0})^{0.5(s_{i1} + s_{i0})}$ where s_{it} is the share of output i in the value of total output in year t; and similarly defined Tornqvist input index.

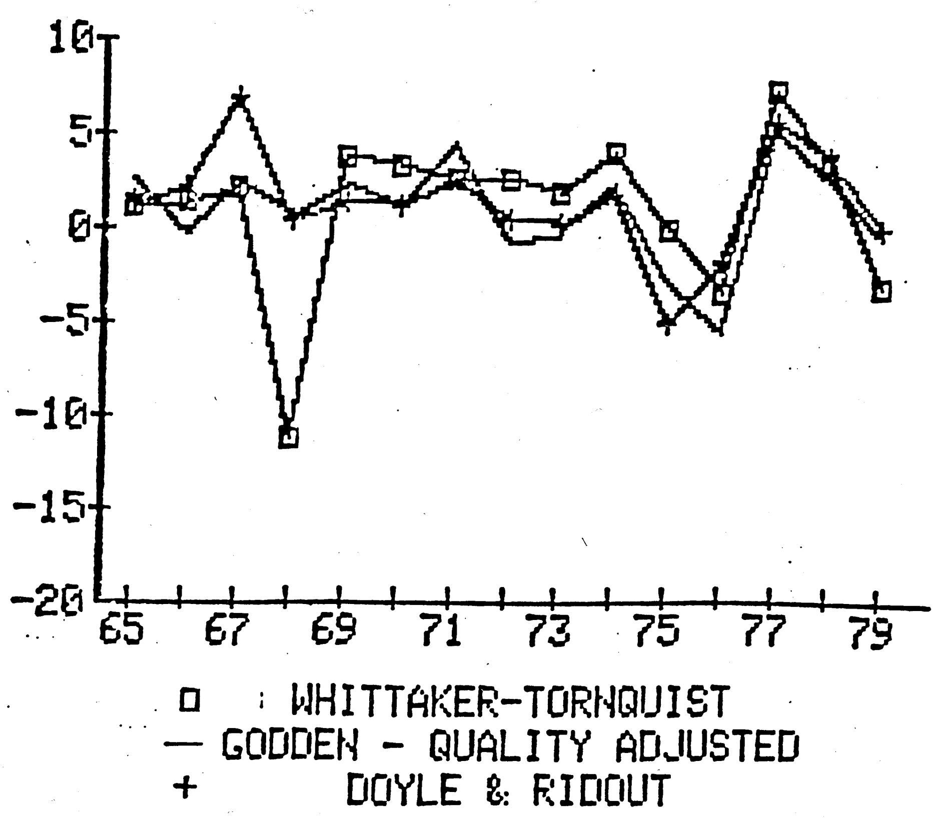
Source: Godden (1985, p.223).

Table III : Comparison of Total Factor Productivity Indices: Correlation Coefficients

	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	-	-	-	-	-

FIGURE 1





From Table 1.

Notes

1. Griliches' (1958) paper on hybrid corn is the classic example. On the cost side there are serious problems in evaluating some inputs such as the contribution of basic or scientific research and the contribution of technology generated by foreign research organisations. Also, the cost of "failures" should be set against the successful project evaluated and expenditures from taxes must include the welfare loss from tax collection (Fox, 1985). Nor are the appropriate shadow prices for the evaluation of benefits agreed upon by all.

2. Technological change is defined as the change in the stock of technology (additions to the blueprints on the shelf). Unfortunately, the term "technical change" has been used both in this way and to mean changes in the technologies of production actually in use, often as measured by changes in output.

3. Innovation may be defined as first commercial use of a novelty, leaving the term invention to describe its actual creation.

4. Citations could be used in this context to allow for differences in quality and/or importance.

5. This ambitious menu still ignores other relationships of great interest, such as that between R and D effort and new technology. See Griliches (1973, 1979, 1984); Sato and Suzawa (1983); Fusfeld and Langlois (1982); Tolley, Hodge and Oehmke (1985).

6. These issues are raised by Sato and Suzawa (1983), who devote a chapter to the relationship between productivity growth and technical change. Learning by doing is the most troublesome notion, when it is an endogenous improvement in the performance of the work force, often called the "Horndal effect" (David 1975, pp.174-6). Should such changes be included in a quality-adjusted labour input series?

7. It is generally not possible to measure both substitution elasticities and biased technical changes from time series data. This result is known as the Diamond-McFadden (1965) impossibility theorem. Binswanger's (1978) solution is to estimate the Allen partial elasticities of factor substitution from cross section data and use these results in calculating the factor-saving biases of technical change.

8. The term is from Walters (1970), who points out that aggregate data of this type contains no information on firm size and hence cannot make any comment on returns to scale in the normal sense.

9. Kislev and Peterson (1981) raise the issue that technical change in the input industries should not be counted as technical change in agriculture. Their influential (1982) paper actually claims to show that there is no technical change in the U.S. agricultural sector.

10. Jorgenson and Griliches (1967) are the best known pioneers of this doctrine which is fully explored in their lengthy debate with Dennison (1964 and 1969 are especially pertinent). Taken literally, the claim that technical change has not been important is at odds with the entire literature of economic history.

11. Kennedy and Thirlwall's (1972) survey argues that the Jorgenson and Griliches approach to productivity measurement "almost amounts to measuring total inputs by output."

12. This amounts to using the cost as a proxy for the unknown value of the research output which is the actual input in the agricultural production process, (as opposed to the technology production process at the research institute).

13. Arithmetic and geometric indices are considered in some detail by Lingard and Rayner (1975). Diewert (1979) provides a comprehensive survey of index number theory. Kendrick (1977) is a very comprehensible general survey.

14. Christensen (1975) discusses the Divisia index and recommends its use by the USDA. It does suffer from one serious defect; it is a line integral and is therefore not path independent and hence can give a nonzero residual in a case where technology is unchanged (Brown and Greenberg, 1984). Hulten (1973) discusses the sufficient conditions for path independence.

15. Selection of a flexible functional form has often been arbitrary, but recent studies show that not all are equally flexible (Lopez, 1985) and the characteristics of the data may mean one form is more representative than another.

16. Input sub-groups that are separable can be aggregated independently, but the assumption of separability imposes restrictions. For instance, the elasticity of substitution between all inputs within the sub-group and all those outside the sub-group must be the same. In practical terms, the illusion that using superlative indices to estimate a flexible functional form imposes no restriction, disappears with the realisation that all empirical tests fail to show separability.

17. The forerunners of this approach are Griliches (1964) and Welsh (1970) who more modestly quality-adjusted the labour input to allow for levels of education. A broad range of quality change problems are addressed in Griliches (1971).

18. This is the value of interest plus depreciation of trucks, tractors and other equipment, deflated by a price series that is admitted to take inadequate account of quality changes. The Bureau of Labor Statistics farm machinery price index is quality adjusted to some extent.

19. Berndt (1980, pp.124-136) argues that the assumption of constant returns is not strictly necessary, but it is normally used to simplify the accounting. Christensen (1975, p.913) argues that if differentiation between returns to scale and technical change is not required, imposing the restriction does no harm; increasing returns will be included in the measure of "technical change". Berndt (1980, p.127) also shows that the index procedure does not impose neutral technical change. The measure will actually be a weighted sum of the input-specific technical change biases.

20. Doyle and Ridout "explain" productivity change by the log of cumulative research expenditures and an index of the weather. They argue that the logarithmic form is "dictated by the data".

21. Godden (1985) offers reasons for the differences.

22. Perhaps this helps explain the pervasive notion of "adverse supply response".

23. Duality theory obviously increases considerably the options as to how estimates may be generated.

REFERENCES

Allen, R.C. and Diewert, W.E. (1981), Direct Versus Implicit Superlative Index Number Formulae, Review of Economics and Statistics, Vol. LXIII, No.3, August, pp. 430-5.

*Ball, V.E. (1985), Output, Input and Productivity Measurement in U.S. Agriculture, 1948079, American Journal of Agricultural Economics, Vol. 67, No.3, August, pp.475-86.

Berndt, E.R. and Christensen, L. (1973), The Internal Structure of Functional Relationships: Separability, Substitution and Aggregation, Review of Economic Studies, Vol.40, pp.403-10.

Berndt, E. R. (1978), Aggregate Energy, Efficiency and Productivity Measurement, Annual Review of Energy, Vol. 3, pp. 225-73.

Berndt, E.R. (1980), Comment, on Gollup, F. and Jorgenson, D., U.S. Productivity Growth by Industry, 1947-73, Ch.1 in Kendrick, J.W. and Vaccara, B. (eds.) New Developments in Productivity Measurement and Analysis, NBER, Chicago University Press.

Biggs, S.D. and Clay, E.J. (1981), Sources of Innovations in Agricultural Technology, World Development, Vol.9, No.4, pp.321-36.

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

*Binswanger, H.P. (1978), Measured Biases of Technical Change, in: Binswanger and Ruttan, Induced Innovation, Ch.7, Johns Hopkins University Press, Baltimore.

Blackorby, C. and Schworm, W. (1984), The Structure of Economies with Aggregate Measures of Capital: A Complete Characterisation, Review of Economic Studies, pp. 633-50.

Blaug, M. (1963), A Survey of the Theory of Process Innovations, Economica, February, pp.13-32.

Brown, M. (1966), On the Theory and Measurement of Technical Change, Cambridge University Press.

Brown, M. and Greenberg, R. (1983), The Divisia Index of Technological Change, Path Independence and Endogenous Prices in: Topics in Production Theory, Forsund, F.R. (Ed.) Macmillan Press, London.

Brown, R.S. and Christensen, L.R. (1981), Estimating Elasticities of Substitution in a Model of Partial Static Equilibrium: An Application to U.S. Agriculture 1947-74, in: Modelling and Measuring Natural Resource Substitution, Ch.10, Berndt, E.R. and Field, B.C. (Eds.) MIT Press.

Caves, D.W., Christensen, L.R. and Diewert, W.E. (1982), Multilateral Comparisons of Output, Input and Productivity using Superlative Index Numbers, Economic Journal, Vol.42, No. 365, March, pp.73-86.

*Christensen, L.R. (1975), Concepts and Measurement of Agricultural Productivity, American Journal of Agricultural Economics, December, pp.910-15.

David, P. (1975) The "Horndal Effect" in Lowell, 1834-56: a Short Run Learning Curve for Integrated Cotton Textile Mills, Ch.3 in David, P. (ed.) Technical Choice Innovation and Economic Growth: Essays on British and American Experience in the Nineteenth Century, Cambridge University Press.

Denison, E.F. (1964), The Unimportance of the Embodiment Question, American Economic Review, Vol.54, March, pp.90-3.

Denison, E.F. (1969), Some Major Issues in Productivity Analysis: An Examination of Estimates by Jorgenson and Griliches, Survey of Current Business, May, pp.1-27.

Desai, M. (1976), Applied Econometrics, Philip Allan, Oxford.

Diamond, P. and McFadden, D. (1965), Identification of the Elasticity of Substitution and Bias of Technical Change: An Impossibility Theorem, Mimeographed, University of California, Berkeley.

*Diewert, W.E. (1976), Exact and Superlative Index Numbers, Journal of Econometrics, Vol.4, January, pp.115-46.

____________ (1978), Superlative Index Numbers and Consistency in Aggregation, Econometrica, Vol.46, pp.883-900.

____________ (1979), The Economic Theory of Index Numbers: A Survey, Discussion Paper 79-09, Department of Economics, University of British Columbia, Vancouver, March.

Dogramaci, A. (1983), Econometric Approaches to Productivity Measurement: A Brief Overview in: Developments in Econometric Analyses of Productivity, Ch.1, Dogramaci (Ed.) Kluwer Nijhoff, Mass. USA.

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

Evenson, R.E. and Kislev, Y. (1975), Agricultural Research and Productivity, Yale University Press, New Haven.

Fettig, L.P. (1963), Adjusting Farm Tractor Prices for Quality Changes 1930-62, Journal of Farm Economics, Vol.45, August, pp.599-611.

Fisher, I. (1922), The Making of Index Numbers, Houghton, Mifflin, Boston.

Fox, G. (1985), Is the United States Really Underinvesting in Agricultural Research,, American Journal of Agricultural Economics, Vol. 66, No.4, November, pp. 806-812.

Fusfeld, H.I. and Langlois, R.N. (1982), Understanding R & D Productivity, Pergamon Press, N.Y.

Fuss, M., McFadden, D. and Mundlak, Y. (1978), A Survey of Functional Forms in the Economic Analysis of Production, in: Production Economics: A Dual Approach to Theory and Application, Ch.II. Fuss, M. and McFadden, D. (eds.), Vols. I and II, North Holland.

*Godden, D.P. (1985), Technological Change and Demand for Output at the Farm Level in U.K. Agriculture 1950-80, Unpublished Ph.D. Thesis, London School of Economics.

Gollop, F.M. and Jorgenson, D.W. (1980), US Productivity Growth by Industry 1947-73, Ch.1 in: New Developments in Productivity Measurement of Analysis, Kendrick, J.W. and Vaccara, B.N. (eds.), NBER, University of Chicago Press.

Griliches, Z. (1958), Research Costs and Social Returns: Hybrid Corn and Related Innovations. Journal of Political Economy, October, pp.419-31.

Griliches, Z. (1960), Measuring Inputs in Agriculture: A Critical Survey, Journal of Farm Economics, Vol.42, December, pp.1411-29.

____________ (1963), The Sources of Measured Productivity Growth: US Agriculture 1940-60, Journal of Political Economy, Vol.71, August, pp.331-46.

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

____________ (Ed.) (1971), Prices, Indexes and Quality Change, Harvard University Press, Cambridge.

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

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

____________ (Ed.)(1984), R & D, Patents and Productivity, University of Chicago Press.

Hayami, Y. and Ruttan, V.W. (1971), Agricultural Development: An International Perspective, First Edition, Johns Hopkins University Press, Baltimore.

____________ (1985) Agricultural Development: An International Perspective, Revised Edition, Johns Hopkins University Press, Baltimore.

Hulten, C.R. (1973), Divisia Index Numbers, Econometrica, Vol.41, pp.1017-26.

Jorgenson, D.W. and Griliches, Z. (1967), The Explanation of Productivity Change, Review of Economic Studies, Vol. 34, pp. 249-83.

Just, R., Zilberman, D. and Hockman, E. (1983), Estimation of Multicrop Production Functions, American Journal of Agricultural Economics, November, pp. 770-80.

Kendrick, J.W. (1977), Understanding Productivity, Policy Studies in Employment and Welfare, No. 31, Johns Hopkins University Press, Baltimore.

Kendrick, J.W. and Vaccara, B. (1980), New Developments in Productivity Measurement and Analysis, NBER, University of Chicago Press.

Kennedy, C. and Thirlwall, A.P. (1972), Surveys in Applied Economics: Technical Progress, Economic Journal, March, pp.11-72.

Kislev, Y.and Peterson, W. (1981), Induced Innovations and Farm Mechanisation, American Journal of Agricultural Economics, Vol. 63, pp. 562-5.

Kislev, Y. and Peterson, W. (1982), Prices, Technology and Farm Size, Journal of Political Economy, Vol. 90, No. 3, June, pp. 578-95.

*Kuznets, S. (1978), Technological Innovations and Economic Growth, in, Kelly, P. and Kranzberg, M. (eds.) Technological Innovation: A Critical Review of Current Knowledge, San Francisco Press.

Lingard, J. and Rayner, A.J. (1975), Productivity Growth in Agriculture: A Measurement Framework, Journal of Agricultural Economics, pp. 87-104.

Lopez, R.E. (1985), Structural Implications of a Class of Flexible Functional Forms for Profit Functions, International Economic Review, Vol.26, No.3, October, pp.592-601.

Mathias, P. (1983), The Machine: Icon of Economic Growth, Ch.3 in Macdonald, S., Lamberton, D. and Mandeville, T. (eds.), The Trouble with Technology: Explanations in the Process of Technological Change, Frances Pinter.

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

Ministry of Agriculture, Fisheries and Food (1969), Productivity Measurement in Agriculture, Economic Trends, CSO.

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.

Norsworthy, J.R. (1984), Growth Accounting and Productivity Measurement, Review of Income and Wealth, pp. 309-29.

Norsworthy, J.R. and Malmquist, D.H. (1983), Input Measurement and Productivity Growth in Japanese and US Manufacturing, American Economic Review, December, pp.947-67.

*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.

Ray, S. (1982), A Translog Cost Function Analysis of US Agriculture 1939-77, American Journal of Agricultural Economics, Vol. 64, No.3, August, pp. 409-98.

Rayner, A.J. (1966), An Econometric Analysis of the Demand for Farm Tractors, Bulletin No. 113, Department of Agricultural Economics, University of Manchester.

Rayner, A.J. and Lingard, J. (1971), Fertilizer Prices and Quality Change: Construction of Fertilizer Price and Quantity Indexes for Great Britain 1956/57 to 1968/69, Journal of Agricultural Economics, Vol. 22, No. 2, May, pp.149-62.

Rogers, E.M. (1983), The Diffusion of Innovations, Free Press, Glencoe, Illinois.

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

Rosenberg, N. (1982), Inside the Black Box, Cambridge University.

*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.

Solow, R. (1957), Technical Change and the Aggregate Production Function, Review of Economics and Statistics, August, pp. 312-20.

Solow, R. and Temin, P. (1985), The Inputs for Growth, Ch.3 in Mokyr, J. (ed.) The Economics of the Industrial Revolution, Allen and Unwin.

Star, S. (1974), Accounting for the Growth of Output, American Economic Review, Vol. 64, pp. 123-35.

Thirtle, C. (1985a), Accounting for Increasing Land-Labour Ratios in Developed Country Agriculture, Journal of Agricultural Economics, Vol. XXXVI, No.2, May.

Thirtle, C. (1985b), The Microecnomic Approach to Induced Innovation: A Reformulation of the Hayami and Ruttan Model, The Manchester School, September.

Thirtle, C. and Ruttan, V.W. (forthcoming), Demand, Supply and Technological Change: a Survey, Gordon and Breach, and in Scherer, F.M. (ed.) Economics of Technological Change, Vol. 31 of the Encyclopaedia of Economics.

Tolley, G.S. (1961), Comment, on Measurement of Labor Input: Some Questions of Definition and the Adequacy of Data, by Denison, E.F. in, National Bureau of Economic Research, Output, Input and Productivity Measurement, Princeton University Press.

Tolley, G.S., Hodge, J.H. and Oehmke (eds.) (1985), The Economics of R and D Policy, Praeger.

*United States Department of Agriculture (1980), Economics, Statistics and Cooperatives Service, Measurement of US Agricultural Research Productivity: a Review of Current Statistics and Proposals for Change, Technical Bulletin No. 1614, Washington, D.C.

Wade, W.W. (1973), Institutional Determinants of Technical Change and Agricultural Productivity Growth: Denmark, France and Great Britain 1870-1965, Unpublished Ph.D. dissertation, University of Minnesota.

Walters, A.A. (1970), An Introduction to Econometrics, Macmillan.

Welch, Finis (1970), Education in Production, Journal of Political Economy, Vol. 78, January/February, pp.35-59.

*Whittaker, J.M. (1983), An Economic Analysis of Productivity Growth in U.K. Agriculture, Unpublished M. Phil Thesis, University of Nottingham.

Zanias, G.P. (1985), Dynamic Interrelated Demand Functions for Factors of Production in United Kingdom Agriculture, Paper presented at the Agricultural Economics Society Annual Conference, Edinburgh.

* Particularly relevant references.