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The rise and fall of public sector plant breeding in the United Kingdom: a causal chain model of basic and applied research and diffusion

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Abstract

This paper examines the barley and wheat breeding programmes of the Plant Breeding Institute (PBI), which was the most successful public plant breeding institute in the UK, until privatization in 1987. The PBI's shares in barley and wheat seed sales are explained, showing that the success with barley was largely a matter of serendipity, whereas the wheat programme followed a more normal pattern. For wheat, the causal chain, or recursive, model decomposes the well-documented link between research expenditures and increases in agricultural productivity into three stages. These are the effects of R&D expenditures on basic research output, measured by publications, the effect of publications and applied R&D expenditures on trial plot yields, and the diffusion of the trial plot technologies, which raises yields on farms. Applying the model to the PBI's wheat varieties allows estimation of the lag structures. In contrast to the results for aggregate agricultural research, for a single plant breeding programme alone there is a considerable lead time before there is any response, followed by a lag distribution only a few years long. The returns to the R&D investments are calculated from the causal chain model, from single equation estimates and by evaluating the yield advantage of the PBI varieties. All three approaches give consistent results, which show that the returns to barley and wheat alone were sufficient to support the entire PBI budget and still give rates of return to applied research of between 14 and 25%. The return to the basic science expenditures of the John Innes Institute has a lower bound of 17%, but must have been even higher than for the PBI if the other Institutes were taken into account. The paper concludes by commenting on the effects of the privatization of the PBI.

Keywords: Barley; Wheat; Breed; Plant breeding institute; R+D lags; Recursive model

1. Introduction

The reductions in UK public sector expenditures in the 1980s included the privatization of the Agricultural and Food Research Council's Plant Breeding Institute (PBI), which was internationally regarded as a highly successful institution. Indeed, the PBI was described as 'the jewel in the AFRC's crown' (Webster, 1989) and at the time it was being split up and privatized, US science policy-makers were advocating the establishment of research stations that

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would emulate the approach of the PBI, with its mixture of molecular biologists and plant breeders (Teich, 1986, Discussion section, p. 108).

The PBI's two greatest successes, in barley and wheat, prove to be quite different. The barley technology was 'on the shelf' before World War II, but did not find an economic niche until the 1950s. The success with barley was used to procure funding for the wheat programme and the varieties were adopted as soon as they were launched. This paper models the PBI's wheat breeding programme and shows that the rate of return (ROR) to this public investment was indeed high. The majority of ROR models reported in the survey of Echeverria (1990) use either economic surplus calculations, or estimates of the elasticity of R&D, derived from the production relationship.

This paper follows the production function approach, but whereas most models use R&D and extension expenditures to explain productivity in a single stage, conflating basic and applied science and diffusion, here the three sequential elements of technical change are modelled by separate equations. The output of basic scientific research is measured by publications and explained by expenditures and the knowledge stock of past publications. Then, applied research expenditures in plant breeding, together with the basic science input of publications are used to explain increases in trial plot yields. Finally, the trial plot yields are the public sector technology input, that in combination with private sector technology (measured by patents) and increased use of fertilizers, lead to improvements in farm yields. Thus, there is a dependent variable for each stage of the process (separate outputs for basic and applied research and diffusion). This gives a three equation causal chain, or recursive, model of basic and applied research and diffusion.

Section 2 provides some background on public sector plant breeding in the UK and analyzes the public sector's share of barley and winter wheat seed sales. Section 3 develops the recursive model and Section 4 explains the data. Section 5 begins with single equation estimates that are used to check for cointegration, before applying the model to the PBI's wheat varieties, as a seemingly unrelated (SURE) system. Section 6 presents ROR calculations which show that public sector plant breeding was a highly profitable investment, even though the lags are longer than in almost all aggregate studies. The economics of the privatization of the PBI is also considered.

2. Public sector plant breeding in the UK

The key institutions for publicly-funded plant breeding research in Great Britain were the PBI in Cambridge, the Welsh Plant Breeding Station (WPBS) in Aberystwyth, the Scottish Plant Breeding Station (SPBS) in Edinburgh, and the John Innes Institute (JII) in Norwich. Table 1 shows the dates when they were established, their locations and the outcome of the reorganization of the system in the mid 1980s, when the institutions were either radically reorganized, privatized or closed. The JII became part of the Agricultural and Food Research Council (AFRC) Institute of Plant Science Research, along with the non-privatized remnant of the PBI, which became the Cambridge Laboratory. The WPBS was incorporated in the AFRC Institute of Grassland and Environmental Research.

The JII was responsible for basic research, but some of its staff moved on to the other three institutions, giving it a training role as well. The plant breeding

Table 1
A succinct history of the plant breeding institutes

Institution	Established	Location	Current status
John Innes Institute	1910	London and Norwich	AFRC centre (1986)
Plant Breeding Institute	1912	Cambridge	Privatized (1987)
Scottish Plant Breeding Station	1921	Edinburgh	Closed (1986)
Welsh Plant Breeding Station	1919	Aberystwyth	AFRC centre (1986)

From the work of Palladino (1996), which provides a history of these institutions.

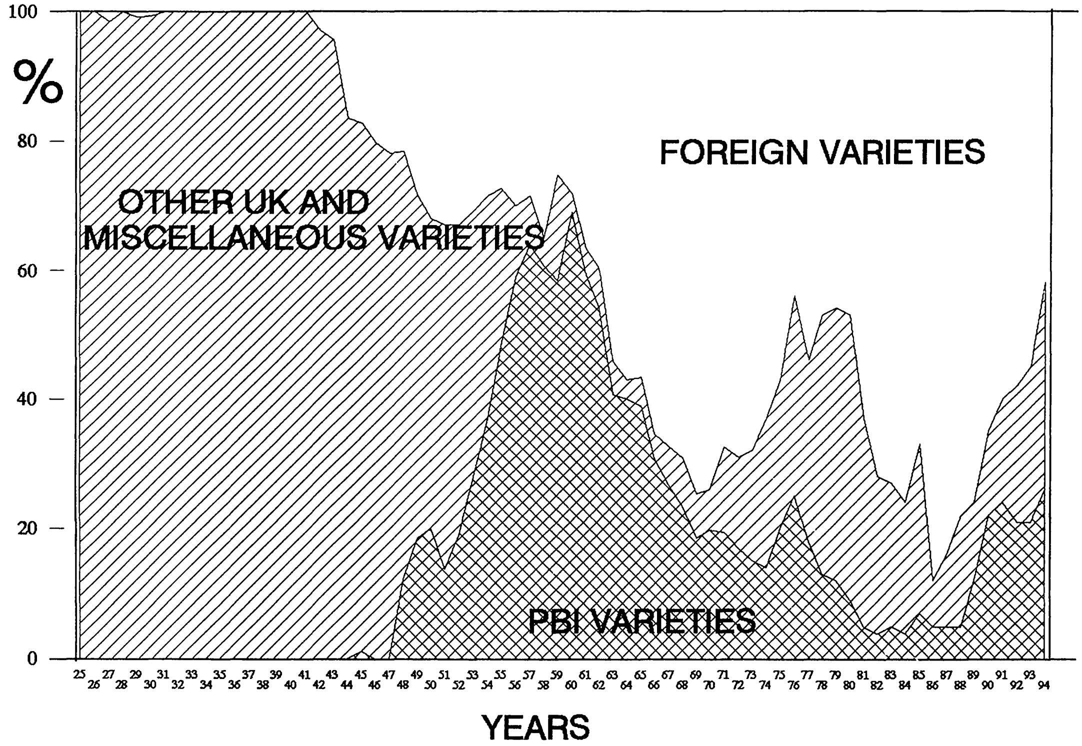

Fig. 1. Market shares for barley seed of other UK producers, the PBI and foreign public and private seed breeders, measured in terms of their shares of UK seed sales, from 1925 to 1994.

institutions tended to specialize in particular crops, including wheat, barley, oats and potatoes at the PBI, grasses and oats at the WPBS, and oats and potatoes at the SPBS. This paper focuses on the PBI's success in producing barley varieties that accounted for 69% of the acreage by 1960 and winter wheat varieties that by 1985 accounted for 92% of the UK market. The other PBI successes were in oat varieties that accounted for over half of UK seed sales by the 1970s but, by then, oats had become a minor crop. Potatoes is a major crop, but the PBI share did not exceed 20% until 1980. Thus, we concentrate on barley and wheat.

Fig. 1 shows the market shares for barley seed of the other UK producers (including private companies, the other public institutions and land race varieties produced by farmers), the PBI and foreign public and private seed breeders, measured in terms of their shares of UK seed sales, from 1925 until 1994. Until the end of World War II, the land race varieties and varieties from private breeders dominated the market.[1] Then, in the decade from 1947, the PBI took the majority share, followed by foreign varieties, leaving almost no share to other UK breeders.

Barley breeding at the PBI before the war (under the directorship of Herbert Hunter, previously with Guinness) focused on the production of malting varieties for the brewing industry. The varieties, released from 1933, were high-yielding, but of poor malting quality and were not adopted by farmers. Then, from the war to 1960, the price of beef and other meats relative to the price of barley increased by about 300%, making it profitable to feed poultry, pigs and beef cattle on

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[1] The exception is Spratt Archer, which accounted for as much as a third of the acreage for some of the period and is the dominant variety. This was bred by the Irish Department of Agriculture and Technical Instruction (in association with Guinness, the brewers), before the creation of the Irish Free State. It is thus included as a UK (public) variety.

barley. Thus, from 1930–1967, the proportion of barley fed to animals increased from 25% to 66% (Britton, 1969). The expanding market for feed grain provided an economic niche for the PBI varieties, as was recognised by Sir G.D.H. Bell (Parliamentary Papers, 1971–1972; p. 93), who was responsible for the breeding of the key variety, Proctor. Changes in the structure of the brewing industry that made malting quality less important, relative to high yields and product uniformity also benefitted the PBI. The results of field trials at the National Institute of Agricultural Botany, various issues [a], National Institute of Agricultural Botany, various issues [b], National Institute of Agricultural Botany, various issues [c], National Institute of Agricultural Botany, various issues [d], National Institute of Agricultural Botany, various issues [e] (NIAB) show that from 1951–1961, the PBI varieties had a yield advantage of almost 0.1 t/ha.

Thus, with the introduction of Pioneer and Earl in 1943 and 1947, and then Proctor in 1953, the PBI moved from a negligible market share to a commanding position in the market during the 1950s. Although it is not possible to model barley with any degree of sophistication, simple estimation does support the historical record. Regressing the PBI share on the price of beef relative to barley, from 1942–1960 gives an adjusted R^2 of 0.8. The Johansen (1988) procedure finds one cointegrating vector and causality tests indicate that the price ratio was Granger prior to the PBI share with lags of two to nine periods.

The success with barley was used in the political marketplace to acquire the funding for expanding the PBI's programmes, especially in wheat breeding. Partly for this reason, the PBI's increasing share of the barley market coincides exactly with the major upturn in R&D expenditures. Regressing the PBI's market share of barley seed sales on the R&D expenditures from 1943–1960 gives an adjusted R^2 of 0.9 and the existence of one cointegrating vector can be established using the Johansen procedure. Given that cointegration implies causality in at least one direction and since the lag between expenditures and effects in plant breeding is well over a decade, the causality must run from the market share to the R&D expenditures.

Then, in the 1960s, the PBI gradually lost its market share as other UK and continental breeders produced higher yielding barleys. By 1971, the PBI share was only 17% and by 1981, it had fallen to 4% as later UK varieties from private breeders (especially Rothwell and Milne) gained market share. By 1986, the total share of the UK breeders was only 11%, which is partly the result of the UK following continental Europe in switching from spring to winter barley. Winter barley increased from 9% of the total in 1971, to 36% in 1981 and 55% by the end of the period. Finally, in the last few years, Fig. 1 shows another rapid change as the new PBI varieties and those of other UK breeders (especially ICI, now Zeneca Seeds) recaptured the majority of seed sales in less than a decade.

Thus, the PBI's initial success with barley is explained by changing relative prices and the success with barley explains the growth of R&D expenditures, which were particularly concentrated on the wheat programme. Fig. 2 shows the changing fortunes of the PBI, the UK private sector and foreign public and private seed breeders, measured in terms of their shares of UK winter wheat seed sales, from the early 1920s until 1995. The changes in market shares can be explained by the success of particular new varieties. During the inter-war period the UK market was dominated by UK private companies, with varieties like Standard Red, Squarehead Master and Victor and the PBI, with Yeoman, Little Joss and Holdfast. From the end of the Second World War to the late 1950s, the share of these varieties began to decline and few successful new varieties were launched, so the market share of foreign breeders increased to over 90%. In particular, French varieties such as Cappelle Desprez and Bersee, along with German and Swedish varieties such as Koga 2 and Atte became increasingly important. It was not until the mid 1960s that the PBI began to recover market share, with the launch of Maris Widgeon in 1963, closely followed by Maris Ranger and Maris Huntsman in 1967 and 1968. By 1974, the PBI had obtained a market share of over 50% and proceeded to dominate the market in the 1980s. In 1985, the PBI varieties accounted for 92% of seed sales and their average market share was 70% from 1974–1995.

At the end of the period, the resurgence of UK private seed breeders is apparent. The figure shows that in sales for the 1995 crop the share of the varieties developed by the PBI fell to about 64%, while the share of other UK companies rose to about 30%. This is almost entirely due to the success of two Zeneca Seed varieties, Brigadier and Hussar. Thus, the dominance of the varieties attributable to the public sector

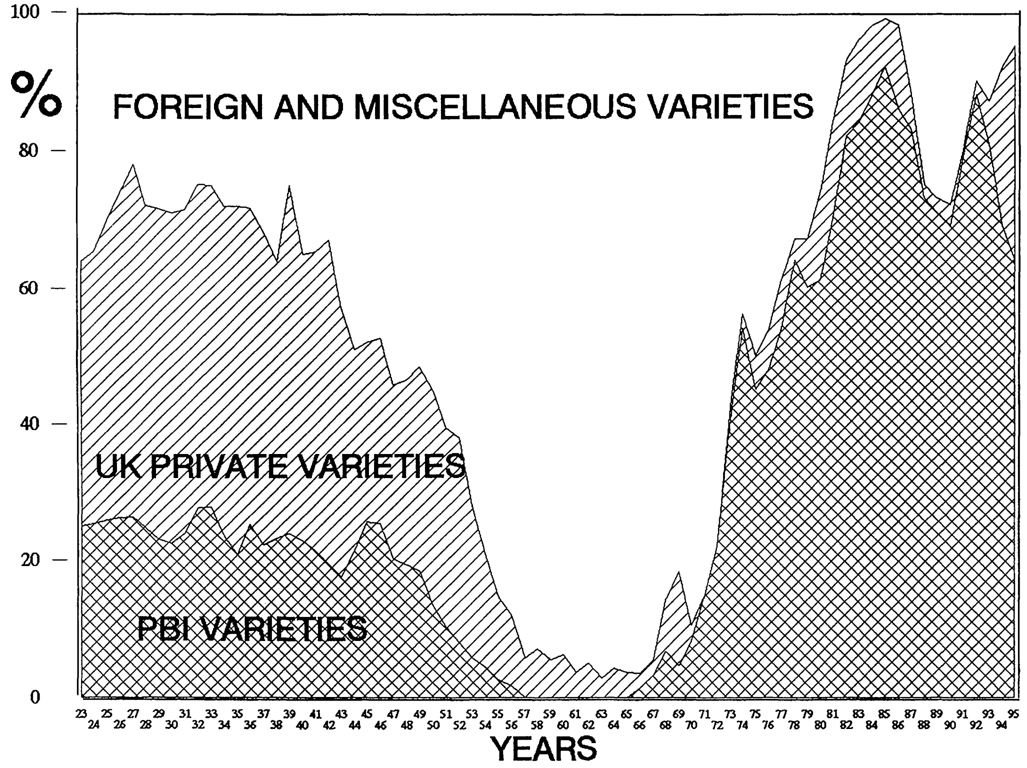

Fig. 2. Changing fortunes of the PBI, the UK private sector and foreign public and private seed breeders, measured in terms of their shares of UK winter wheat seed sales, from the 1920s to 1995.

appears to be at an end and a new era is beginning in which the multinationals, who invested in the industry in the 1980s,[2] will play a major role.

Fig. 3 shows that the growth of the PBI's wheat market share, from 1965, is closely correlated with lagged R&D expenditures. Real expenditures increased rapidly, from the late 1940s, and was soon under the auspices of the recently-established Agricultural Research Council (which later became the AFRC). From 1967 to 1986, when Swedish and German varieties took a larger segment of the market, a simple regression shows that PBI R&D expenditures, lagged 19 years, explains 97% of the variance in market share. The standard tests establish that there is a cointegrating vector and that R&D is causally prior to the PBI share.

These results are tentative evidence of the time lag between applied research expenditures and tangible gains in the market place. The 19-year lag is the sum of the innovation lag for applied research (from expenditures, to the trials of new varieties) and the diffusion lag (from release, to the time that varieties gained acreage share on UK farms). Section 3 formalises these relationships by developing the recursive model.

3. A recursive model of basic and applied research, and diffusion

The data described in Section 4 allow a novel approach. The output of the JII can be measured by its scientific publications. These in turn are inputs in the PBI's plant breeding programmes, where the out-

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[2] In 1987, Unilever bought the PBI and ICI bought Milne Masters, an old-established breeding company, then owned by the Swedish sugar beet breeders, Hilleshog, who are now part of Sandoz. Similarly, Shell purchased Nickersons, which was one of the largest UK breeders.

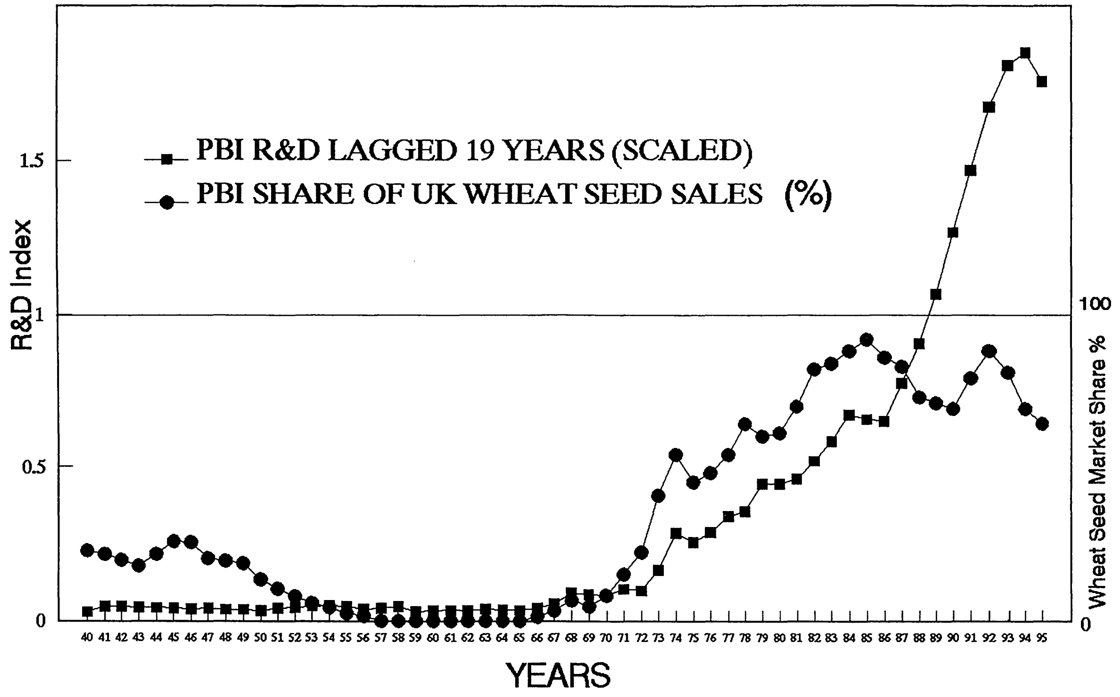

Fig. 3. Growth of PBI's wheat market share.

put of new technology can be measured by the increase in trial plot yields for the PBI's new varieties. Thus, the lagged effect of the basic R&D on knowledge production and applied R&D expenditures on plant varieties can be separately determined, before going on to estimate the diffusion lag, in the final stage of the model. Throughout the analysis, all of the variables are in logarithms, so the parameters are elasticities.

The first equation, for the production of the *basic research* process makes the publications of the JII (PJI) a function of its own R&D expenditures (RDJI), with lags of 1 to F years, past publications, with lags of 1 to G years, a constant and a stochastic error.

$$\mathrm{PJI}_t=\alpha_1+\sum_{f=1}^{F}\beta_{1f}\,\mathrm{RDJI}_{t-f}+\sum_{g=1}^{G}\gamma_{1g}\mathrm{PJI}_{t-g}+\varepsilon_{1t} \quad (1)$$

In the *applied research* equation, trial plot yields, (TPY), are a function of the input of scientific knowledge (PJI), lagged from 1 to H years and of the PBI's own R&D expenditures (RDPBI), lagged from 1 to I years, fertilizer use (FERT), lagged 1 year, a constant and an error.

$$\mathrm{TPY}_t=\alpha_2+\sum_{h=1}^{H}\beta_{2h}\,\mathrm{PJI}_{t-h}+\sum_{i=1}^{I}\gamma_{2i}\mathrm{RDPBI}_{t-i} + \delta_{21}\mathrm{FERT}_{t-1}+\varepsilon_{2t} \quad (2)$$

The *diffusion* equation makes farm yields, (FY), a function of trial plot yields (TPY), with lags of 1 to J periods, fertilizer use (FERT), with a lag of 1 year,[3] chemical patents pertaining to agriculture (CHEM), with lags of 1 to K years, a constant and an error term.

$$\mathrm{FY}_t=\alpha_3+\sum_{j=1}^{J}\beta_{3j}\,\mathrm{TPY}_{t-j}+\delta_{31}\,\mathrm{FERT}_{t-1} + \sum_{k=1}^{K}\gamma_{3k}\mathrm{CHEM}_{t-k}+\varepsilon_{3t} \quad (3)$$

This system of equations is not simultaneous, since all the right-hand side variables are predetermined, due to the lags. Thus, the equations are a causal chain,

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[3] Fertilizer application for winter wheat is mainly at planting, in October; the crop is harvested in July/August.

or recursive model and may be estimated as single equations, or as a SURE system, if the errors across equations are correlated. The issue of the appropriate specification and method of estimation is pursued in Section 4.

The model is based on strong priors, due to the considerable historical detail available, but a range of alternative formulations, were tested empirically. For instance, interviews with the surviving breeders suggested that the UK plant breeding institutes and the JII traded information, but that there was very little contact with, or input from, other countries, such as the USA. The genetic materials used were largely British and European and this was confirmed by tracing the parentage of the varieties.

In Eq. (1), a major difference between the production of scientific knowledge and most other production processes is that the output (the addition to the knowledge stock) in period t will depend on accumulated past output (the knowledge stock at the beginning of the period). Lagging PJI two periods in the basic research equation, proved to be the best representation of the knowledge stock, performing better than pre-constructed stock variables, such as moving averages and perpetual inventory models.

The applied research equation is actually less simplistic than it appears, since the influence of the weather has been removed prior to testing and estimation. This is done by regressing the TPY of *old* winter wheat varieties on a time trend and retrieving the residuals, which may be called a yield deviation weather index. Then, the *new* TPY are regressed on this index and the retrieved residuals are the weather-free TPY. This two stage approach proved superior to adding a weather variable to the yield equations. Fertilizer data for the trial plots is not available (Godden, 1988), so it is assumed that fertilizer use on trial plots follows the same pattern as on farms.

The FY in the diffusion equation have had the influence of the weather removed in the same way as for TPY, but using farm-level barley yields because the trial plot information is too location-specific to represent the whole UK winter wheat area. Fertilizer application rates for winter wheat, at the farm level, are used in both Eqs. (2) and (3). Private sector research expenditures are not available, so the private sector technology input is represented by chemical patents pertaining to agriculture, registered in the USA. Thus, some account is taken of progress in plant breeding outside the UK. Lastly, the recursive model has the advantage of separating the collinear variables involved in the three processes, thus giving more robust results. Although the explanatory variables in Eqs. (1) and (2) can be substituted into Eq. (3), to give a single Eq. (4),

$$\mathrm{FY}_t = \alpha_4 + \beta_{4m}\mathrm{RDJI}_{t-m} + \sum_{n=1}^{N} \gamma_{4n}\mathrm{RDPBI}_{t-n} + \sum_{p=1}^{P} \phi_{4p}\mathrm{PJI}_{t-p} + \delta_{41}\mathrm{FERT}_{t-1} + \sum_{q=1}^{Q} \psi_{4q} \quad (4)$$

both John Innes publications and chemical patents proved to be insignificant in this model. Thus, the causal chain model is preferred partly because it overcomes this difficulty. However, Eq. (4) is useful since it provides a direct link between the R&D expenditures and FY, which makes the calculation of rates of return straightforward.

4. Data

Several measures of the inputs and outputs of the research institutes were compiled. Data on the scientific publications, research expenditures and number of personnel employed (not used in the reported results) for the four institutes were assembled directly from their archives, for the period 1920 to 1980. These were updated to 1986/1987, when the Institutes were reorganised, using the Annual Reports of the AFRC, the JII and the PBI. Since there is no research deflator that covers the period, the expenditure series were converted to constant Pounds using a general price deflator. The series are total expenditures, but the rapid growth in PBI expenditures during the post-war period was closely related to the wheat breeding programme, which is a major reason for concentrating on wheat.

The 'technology output' of the PBI is measured by TPY for *new* varieties of spring and winter barley and winter wheat, tested at Cambridge, which are reported in numerous issues of the National Institute of Agricultural Botany, various issues [a], National Institute of Agricultural Botany, various issues [b], National Institute of Agricultural Botany, various issues [c], National Institute of Agricultural Botany, various issues [d], National Institute of Agricultural Botany, various issues [e] Journal, supplemented by Godden (1987), NIAB Bulletin of Crop Varieties and Seeds, NIAB Classified List of Cereal Varieties, England and Wales and NIAB Farmer's Leaflet No. 8. Where possible, new varieties are defined as those PBI varieties being tested by NIAB prior to their official launch date in the UK. The wheat data cover the period from 1947 to 1995, because there were no new varieties tested from 1938 to 1946. In the early part of the period, the new varieties are mostly not from the PBI, but were included so that the lag length is not predetermined by the start of the estimation period. From 1964 onwards, there are always PBI varieties, but later on, the definition of a new variety becomes a matter of judgement, after changes in NIAB reporting procedures. Data on TPY for *old* (post-release) winter wheat varieties were collected, from the same sources and used to remove the influence of the weather.

The FY for wheat are from Ministry of Agriculture Fisheries and Food (1967), updated using data from Ministry of Agriculture Fisheries and Food, various issues. Similar data for barley were collected from the same sources, again to remove the effects of the weather. The data for fertilizer use on winter wheat begin in 1943 and were constructed from the works of Archer (1985), Keatley (1976), Fertilizer Manufacturers Association (various years) and Fertilizer Manufacturers Association/ADAS (various years).

The market shares of the public-sector institutes, the UK private, foreign private and public firms, up to 1970, (used in Figs. 1 and 2) were constructed from the percentage of trial plots allocated to specific varieties, as reported in the NIAB Annual Report and Accounts (various years) and NIAB Bulletin of Crop Varieties and Seeds (various issues). Given that farmers request that NIAB undertakes trials of particular varieties, these figures are a good leading indicator of the usage of specific varieties on farms. Indeed, NIAB suggest that they indicate the popularity of varieties. From 1971 onwards, actual sales of seeds, by variety, are available from the Home Grown Cereals Authority (various years). These data tend to overstate the shares of new varieties, as sales account for about 70% of the acreage. The remaining 30% is planted with seed retained from the previous harvest, in which the older varieties tend to predominate.

5. Estimation

As a preliminary step, the single equations are fitted separately, which has the advantages of allowing the full duration of the data to be used, with different time periods for each equation. Careful examination of the data duration and the lags is needed to determine the different estimation periods. The single equations allow tests to establish that cointegrating vectors exist, but it is not permissible to include distributed lags in the cointegration tests, so single values are used to capture the peak effects for the lagged variables. This is an essential exploratory step with these unusual data and unconventional model, since determining valid relationships from a simultaneous system with distributed lags is extremely difficult. Having established cointegration and demonstrated that the model is valid, the parameter estimates from the SURE model are preferred. They incorporate polynomial lag structures and the model takes account of the non-zero covariances across equations, thus producing more efficient estimates.

The results of both the Dickey–Fuller (Dickey and Fuller, 1981) (DF) test and Johansen (1988) maximum likelihood tests reported in Table 2 indicate that there are cointegrating vectors for all of the equations in the model. The values of the Durbin Watson statistics also confirm cointergration, according to the cointegrating regression Durbin Watson (CRDW) test of Sargan and Bhargava (1983), since the critical value for the shortest series is close to unity and the lowest test statistic is 1.6.

The first section of Table 2 reports the OLS results for the basic science Eq. (1), fitted from 1922 to 1987, which is the data period adjusted for the lags. The first row shows that 83% of the variance in John Innes publications is explained and the Durbin Watson statistic indicates no serial correlation. The Durbin h statistic, which is the appropriate test statistic for serial correlation with one lagged dependent variable is -1.1740, against a 95% critical value of about -1.645, as the distribution is asymptotically normal. Thus, a single lag of the dependent variable is sufficient to ensure that there is no serial correlation, but the second lagged term is significant and is justified by the argument that existing knowledge is an important input into the production process.

Table 2
Single equation OLS results and cointegration tests

Var	Lag	Coefficient	*T*-statistics	DF Test	Johansen model	
					Eigenvalue test	Trace test
EQ (1): Basic science, 1922–1987, Dependent Var PJI, R^2=0.83, DW=1.9028 Durbin h=−1.174						
RDJI	1	0.148	2.07	−7.801 (−4.26)	18.21 (15.67)	21.15 (19.96)
PJI	1	0.448	3.87			
PJI	2	0.384	3.36			
EQ (2): Applied science, 1947–1995, Dependent Var TPY, R^2=0.92, DW=1.9243						
PJI	14	0.080	2.55	−7.62 (−4.34)	45.87 (18.03)	99.86 (49.92)
RDPBI	11	0.106	3.97		25.77 (14.09)	53.99 (31.88)
FERT	1	0.124	2.07		18.00 (10.29)	28.22 (17.79)
					10.23 (7.50)	10.23 (7.50)
EQ (3): Diffusion, 1953–1995, Dependent Var FY, R^2=0.96, DW=1.6037						
TPY	5	0.162	1.75	−5.18 (−4.39)	37.78 (19.88)	87.74 (58.96)
FERT	1	0.387	5.73		21.85 (16.13)	49.96 (39.08)
CHEM	6	0.075	1.66		19.81 (12.39)	28.11 (22.95)
EQ (4): ROR model, 1947–1995, Dependent Var FY, R^2=0.98, DW=1.6880						
RDJI	21	0.068	1.88	−5.61 (−4.33)	61.90 (28.14)	108.10 (53.12)
RDPBI	16	0.069	3.18		27.29 (22.00)	46.19 (34.91)
FERT	1	0.298	11.84			

The values of the constants are not reported.
The OLS residual tests and Johansen critical values are for 95% significance.
The specification of VAR lengths in the Johansen models are determined using the Schwarz criterion.

Since all the variables are in logarithms, the coefficients should be interpreted as output elasticities. All are in the correct range, between zero and unity and significantly different from zero at the 97.5% confidence level (a one-tailed test is appropriate, since the elasticities cannot be negative). The output elasticity of R&D, lagged one period, is 0.148 and the short lag between R&D expenditures and research output is possible, since most new employees would have completed their studies at university and should begin producing straight away. From the point of view of the structure of the model, R&D is weakly exogenous, because it is predetermined. Applying the DF test for stationarity to the OLS residuals suggests that this equation cointegrates in the levels, supporting the Johansen (1988) test results in the last column. In both tests, a cointegrating vector exists if the absolute value of the test statistic is larger than the critical value, shown in brackets. The lagged dependent variable was not included in the Johansen or CRDW tests.

The next section of Table 2 reports the results for the plant breeding equation. Over 90% of the variance in TPY is explained and there is no evidence of serial correlation, or other problems. The output elasticities for John Innes publications and the PBI R&D expenditures are in the correct range and significantly different from zero. Fertilizer is included to avoid the possibility of an upward bias to the technology coefficients, since it is positively correlated with R&D, but it actually has very little impact on the other results. The lag lengths are determined using the Akaike and Schwarz criterion and are found to be 14 years for JII publications and 11 years for the PBI's R&D expenditures. The tests select the most powerful lag relationships, which are shown below to be the peak values of the polynomially distributed lag (PDL) structures. Eq. (2) cointegrates according to all the tests. The Johansen model finds four cointegrating vectors, which indicates a strong and stable link between TPY and the inputs of JII publications and PBI's R&D expenditures. Multiple vectors frequently indicate feedbacks, but in this case, causality tests over all lag lengths, for all the variables, found only two feedback effects. With a one period lag, PBI R&D was causally prior to John Innes publications and with three and 5-year lags, FY were prior to John Innes

R&D. However, both variables were insignificant in the estimating equations, so the model is assumed to be adequate. The assumption of exogeneity implicit in the causal chain model holds in this case, because the explanatory variables are again lagged and hence predetermined.

The same approach is applied to the diffusion Eq. (3), and the results are reported in the third section of Table 2. The adjusted R^2 is 0.96, with an elasticity of 0.16 for TPY, lagged 5 years, 0.39 for fertilizer, lagged 1 year and 0.075 for chemical patents, lagged 6 years. This is a reasonable lag length for diffusion of trial plot technology to the farms and the short lag from patenting to peak effects for private sector technology is also believable. The tests all indicate that cointegrating vectors exist and that there is a strong relationship between FY, TPY and fertilizer use.

The composite ROR Eq. (4) has longer lags from R&D expenditures to the peak effects on FY, which is to be expected since the diffusion lag of 5 years is included. For the PBI R&D, the peak lag of 16 is exactly the sum of the lag from expenditures to TPY and from trial plot to FY. For John Innes R&D, the 21-year lag is 2 years longer than the sum indicated, which is probably due to the very different estimation period, which was determined by data availability. The John Innes publications and the chemical patents variable were not significant and a joint deletion test confirmed that they had no explanatory power, so they were dropped from this model. Again, all the tests confirmed the existence of cointegrating vectors.

These single equation results suggest that the regressions are not spurious and that the parameter estimates are robust. However, the single equations do not model the lag structures and cross-equation correlations of the error terms are not taken into account. SURE regression is the appropriate model in these circumstances, but can only be fitted to the period for which all the variables are available, which is 1954 to 1987. For Eq. (4), which does not require TPY, the estimation period is 1947 to 1995, which is a substantial increase in observations, of almost 50%.

Table 3 reports the results of the SURE model for Eqs. (1)–(3), showing that the shorter estimation period, modelling the lag distributions and the corrected covariance matrix of the SURE system do change some of the elasticities, but the outcome is not fundamentally different from the single equation approach. Comparing Tables 2 and 3 shows that the elasticities for both variables in Eq. (1) have increased, despite keeping the same lag structure, whereas allowing for second degree PDLs, with lead times, in Eq. (2) hardly increases the two key R&D elasticities. The biggest change is for TPY in Eq. (3), where the 8-year PDL increases the elasticity of FY with respect to TPY to 0.736, which matches the PBI's

Table 3
SURE results for the recursive system, 1953–1987

Equation	Variable	Coefficient	*T*-statistics	DW	Adj. R^2
(1) Basic science, dependent variable is PJI (John Innes Publications)	constant	$\alpha_1=-3.91$	−2.57	1.70	0.78
	RDJI (lag 1)	$\beta_1=0.370$	2.62		
	JIPUB (lag 1)	$\gamma_1=0.524$	2.94		
	JIPUB (lag 2)	$\delta_1=0.311$	1.80		
(2) Applied science, dependent variable is TPY (Trial Plot Yields)	constant	$\alpha_2=-2.09$	−17.95	1.98	0.91
	PJI lags, 11-year lead, 6 years of lags	$\Sigma\beta_2=0.094$	2.31		
	RDPBI lags, 9-year lead, 5 years of lags	$\Sigma\gamma_2=0.108$	3.65		
	FERT (lag 1)	$\delta_2=0.116$	1.84		
(3) Diffusion, dependent variable is FY (Farm Yields)	constant	$\alpha_3=-1.27$	−3.65	1.77	0.97
	TPY lags, 8 years of lags	$\Sigma\beta_3=0.736$	5.33		
	FERT (lag 1)	$\delta_3=0.293$	4.40		
	CHEM (lag 5)	$\gamma_3=-0.009$	−0.35		

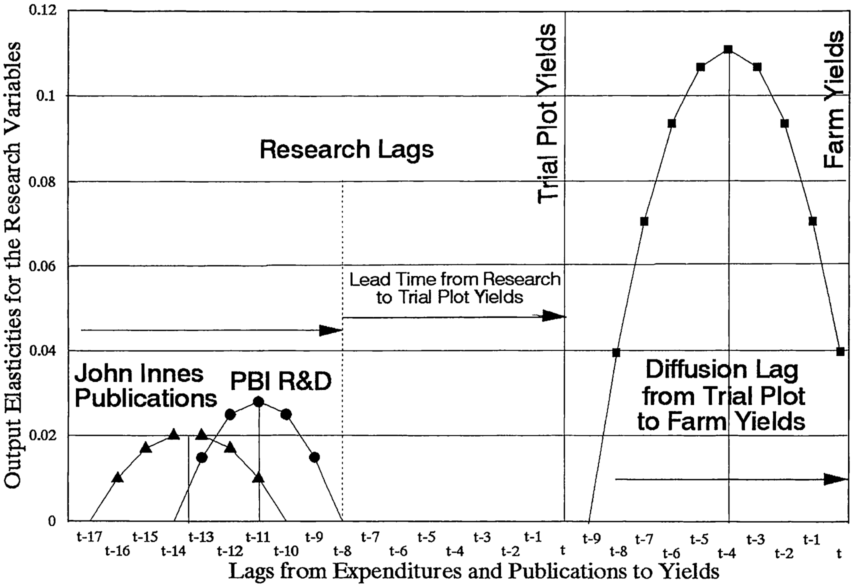

Fig. 4. Individual lag coefficients for Eqs. (2) and (3).

acreage share once their varieties became established in the mid 1970s. This increase is at the expense of fertilizer, which has a lower elasticity and chemical patents, which are now insignificant, regardless of how they are modelled.

It is the total elasticities that are reported for the distributed lag variables, but the individual lag coefficients for Eqs. (2) and (3) are shown in Fig. 4. Before fitting the SURE model and including distributed lags in Eq. (4), the lengths of the lags were determined by estimating unrestricted finite lag models. The lag length is found by searching over a range of lags, again using the Akaike and Schwartz criteria. For the basic science equation, only lags of one and two periods mattered.

In the applied science equation, the tests suggested a lead time of 9 years before the PBI expenditures have any significant effect on TPY (lead time in Fig. 4). Then, including lags from 9 to 13 years, with a second degree polynomial distribution, gave the best test statistics.[4] For the John Innes publications, the lead time was 11 years and including lags from 11 to 16 years, with a second degree polynomial distribution, gave the best results. These lag distributions, from the SURE model, shown in Fig. 4, are quite different from the results at the national aggregate level, where there is normally no lead time.

Last, for the diffusion equation, the lag from TPY to FY was 8 years, again assuming a second degree polynomial distribution. This is the diffusion lag, linking TPY to FY in Fig. 4. The horizontal axis in Fig. 4 is deliberately split, to indicate that the lags are not additive. Indeed, the figure shows that the peak effect in the diffusion lag is at 4 years. For chemical patents the preferred model used a single lag of 5 years, but neither this nor distributed lags made the variable significant.

The results for the single equation version of the model, with polynomial lags, are reported in Table 4, which confirms the explanatory power of the model and the stability of the coefficients. The John Innes elasticity is almost unchanged from the SURE results and the rather lower PBI elasticity is a result of the shift from trial plot to FY, as the ROR calculations in the next section will show.

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[4] Discussions with plant breeders who are familiar with the institution and the period led to a consensus that, from inception to release, plant breeding programs took about 12 years.

Table 4
Single composite equation, ROR model, 1947–1995

Equation	Variable	Coefficient	T-statistics	DW	Adj. R_2
(4) ROR, dependent variable is FY (Farm Yields)	constant	α_4=−2.99	−10.72	1.65	0.98
	RDJI lags, 18-year lead, 8 years of lags	$\Sigma\beta_4$=0.096	2.25		
	RDPBI lags, 13-year lead, 7 years of lags	$\Sigma\gamma_4$=0.065	2.81		
	FERT (lag 1)	δ_4=0.282	11.35		

The peak lag lengths are consistent with the results of the SURE model of Table 3 and the cointegration tests of Table 2. For John Innes R&D the lead time is 17 years, followed by a 8-year PDL, the coefficients of which are shown in Fig. 5. The peak effect is at 21 and 22 years, which corresponds to the one or two lags in Eq. (1), plus 13 or 14 in Eq. (2), plus the 4-year peak diffusion lag in Eq. (3), which sum to 20 years. For the PBI expenditures, the lead time is 12 years, followed by a 7-year PDL. The peak is at 16 years, as compared with the SURE model results, shown in Fig. 4, of an 11 year research lag, plus a 4-year diffusion lag.

The lead times in this model help to explain why Khatri (1994) found that for the UK, the lag distribution for agricultural output as a function of national R&D distribution has a very strong negative skew, with a peak at 16 years and a total length of 19 years. Indeed, these results for plant breeding alone suggest that the UK lag is still being truncated due to lack of data, since the series are available only from 1954 to 1990. Using these data, Khatri and Thirtle (1996) show that the national ROR appears to be almost 18%. Section 6 produces estimates of the RORs to John Innes and PBI expenditures on plant breeding.

6. The returns to basic and applied research in plant breeding

For barley, there is no estimated output elasticity for R&D, but the data available allow a calculation of the

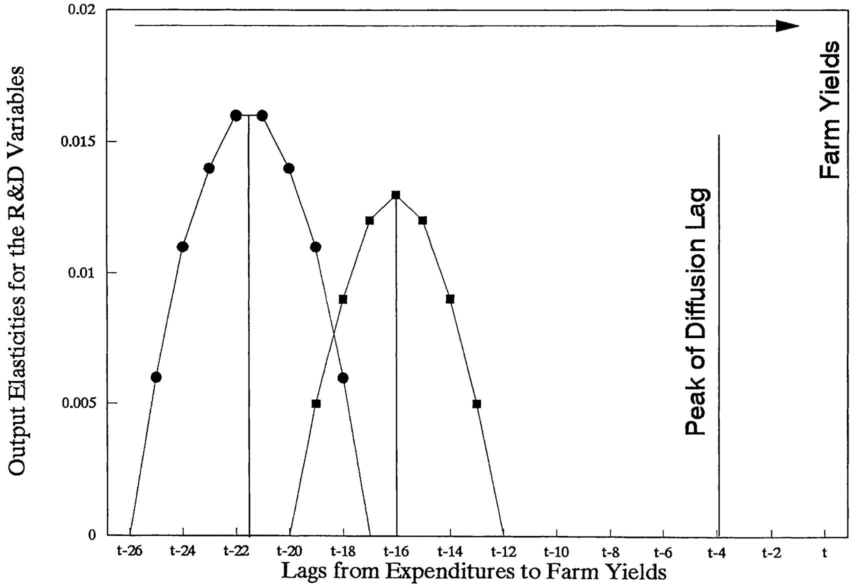

Fig. 5. Coefficients of the 8-year PDL that followed the 17-year lead time for John Innes R&D.

ROR to the barley programmes. The NIAB field trials (Bulletin of Crop varieties and Seeds, various issues) show that the PBI varieties enjoyed a 0.09 tons per hectare average yield advantage over the competing varieties, from 1951–1966. This yield advantage, multiplied by the price of barley and by the PBI's share of the area harvested gives a simple measure of the social benefit. If this benefit is set against all the expenditures of the PBI, from 1920–1947, allowing for a 25-year lag, the marginal internal rate of return (MIRR) is 16%.

Applying this simple method to the wheat programmes provides a check on the more sophisticated calculations made below. This approach has the advantage of explicitly incorporating the counterfactual history, in the sense that had the PBI not existed, there were foreign and other UK varieties available and only the marginal increment in yields should be counted as a social benefit. The average yield advantage of the PBI wheat varieties, from 1965, based on the NIAB field trials was 0.1 t/ha, which gives a MIRR of 14%.

The ROR calculation based on the estimated coefficients of R&D is explained in Thirtle and Bottomley (1989). The coefficients of the R&D variables in Eq. (4) are output elasticities relating basic and applied R&D expenditures to FY and can be converted to value marginal products (VMPs) to allow calculation of the social MIRR to R&D. The calculations from Eq. (4) are straightforward. For the John Innes expenditures, the elasticity, denoted $\beta_{4\mathrm{m}}$ may be expressed as:

$$\beta_{4m} = \frac{\partial \ln \mathrm{FY}_t}{\partial \mathrm{RDJI}_{t-m}} = \left[\frac{\partial FY_t}{\partial \mathrm{RDJI}_{t-m}}\right]\left[\frac{\overline{\mathrm{RDJI}}_{t-m}}{\overline{\mathrm{FY}}_t}\right] \qquad (5)$$

where $\overline{\mathrm{RDJI}}$, $\overline{\mathrm{FY}}$ can be viewed as mean values, so that multiplying by the inverse of these mean values in Eq. (6) gives the marginal product of John Innes R&D in year *t–m*.

$$\mathrm{MP}_{\mathrm{RDJI}_{t-m}} = \beta_{4m}\left[\frac{\overline{\mathrm{FY}}_t}{\overline{\mathrm{RDJI}}_{t-m}}\right] \qquad (6)$$

However, Eq. (6) is still in terms of the effect of R&D on FY, and for a ROR to be calculated, the change in productivity must be converted into a value. Multiplying Eq. (6) by the price of wheat (P_{W}) gives the gain per hectare and multiplying by the acreage (AREA) converts it to the value of the gain to UK agriculture.

$$\mathrm{VMP}_{\mathrm{RDJI}_{t-m}} = \beta_{4m}\left[\frac{\overline{\mathrm{FY}}_t}{\overline{\mathrm{RDJI}}_{t-m}}\right](\mathrm{P_W})_{t-m}(\mathrm{AREA})_{t-m} \qquad (7)$$

The MIRR to a £1 increase in R&D can be calculated from Eq. (7) by summing the discounted flow of cash benefits,

$$\sum_{m=1}^{M}\left[\frac{\mathrm{VMP}_{t-m}}{(1+r)^m}\right] - 1 = 0 \qquad (8)$$

in which, *m* is the length of the lag, for each expenditure term, and the MIRR for a one unit change in R&D expenditure is calculated by solving for *r*.

The results of these calculations show that even if the entire R&D expenditures of the JII, since World War 2, are set against the return on wheat alone, the MIRR is 19%. In fact, the calculation is quite insensitive to the R&D expenditures, both because they are small relative to the value of the yield increases and because of discounting for so many years. Thus, if the JII R&D expenditures attributed to wheat are assumed to be proportional to wheat's share in the value of field crop output (about 25%), the MIRR only rises to 32%. So, however the calculation is made, basic science appears to generate high social rates of return, even without taking the successes of the Scottish and Welsh PBIs into account.

Calculated in the same way, the MIRR for the PBI's applied R&D expenditures, attributing all the expenditures from 1948 onwards to the wheat programmes, is 22%, over the period 1948 to 1995. Thus, although the total elasticity is lower than for John Innes expenditures, which are of a similar magnitude, the shorter lag more than compensates, to give a slightly higher ROR. Again, the MIRR is not sensitive to changes in expenditures. For example, if Eq. (9) is adjusted to include only the PBI's share of the acreage, the MIRR falls to 17%, but this is an example rather than a recommended adjustment, since we argue below that the acreage share has already been taken into account in the elasticity estimates. Alternatively, if only 50% of expenditures are attributed to the wheat programmes, the MIRR increases only to 28% and if only 25% of the expenditures are allocated to wheat, the MIRR is 33%. Again, it is clear that the social ROR to plant breeding R&D is high, however the calculation is formulated. Thus, the PBI wheat programmes are an unqualified success, when judged by the usual social ROR criteria.

It is not so obvious how the elasticities should be derived from the recursive model. For the easier case of the PBI R&D expenditures, the output elasticity from Eq. (2), which is with respect to TPY, is converted to a marginal product and to a value, in the usual way. The only additional transformation is to multiply by the output elasticities of TPY from Eq. (3), to allow for the fact that a 1% increase in TPY gives only a 0.736% increase in FY. This value makes good sense, since the PBI's share of the acreage averages a little over 70% from the mid 1970s. Thus, the calculation is

$$\mathrm{VMP}_{\mathrm{RDPBI}_{t-i-j}} = \left[\sum_{i=1}^{I}\gamma_{2i}\right]\left[\frac{\overline{\mathrm{TPY}}}{\overline{\mathrm{RDPBI}}}\right]\left[\sum_{j=1}^{J}\beta_{3j}\right] \times (P_{\mathrm{W}})_{t-i-j}(\mathrm{AREA})_{t-i-j} \qquad (9)$$

where the lag for each year t is i plus j, because of the sequential nature of the causal chain model. This has to give almost exactly the same ROR, since the total R&D elasticity in Eq. (2) is 0.108 and the total TPY elasticity in Eq. (3) is 0.736. The product is 0.079, as compared with the direct R&D elasticity in Eq. (4) of 0.65, for the longer period which includes low shares at the beginning of the period.

Thus, the causal chain elasticities give a MIRR of 24%, for the period 1953 to 1987, and the single equation model, for which the specification is more dubious, does seem to give the same results as the preferred model, for which the ROR calculation is less well established. Together, the results give some cause for at least a modest level of confidence.

For the John Innes R&D expenditures, where the elasticities run from Eqs. (1)–(3), the appropriate calculation from the recursive model is somewhat speculative, but the same rationale should apply, with one more step. Suppose that the elasticity of John Innes R&D calculated from the causal chain should be approximately equal to the direct estimate of 0.096. From Eq. (1), the R&D elasticity must be added to the elasticities of the publications, which are the knowledge stock, created by past R&D. This sum, of 1.205, multiplied by the publications elasticity in Eq. (2) of 0.094 and finally by the trial plots elasticity, from Eq. (3), of 0.736, gives a product of 0.083, which is reasonably close. If this is accepted, then following Eq. (9), the first term in Eq. (10), below, is the marginal physical product of R&D in terms of publications. The next term (from Eq. (1)) allows for the effect of past R&D by including lagged publications, the next, from Eq. (2), converts from publications to TPY and the next, from Eq. (3), converts from TPYs to FY. Finally, the price of wheat and the area convert the expression into a total value of the gain.

$$\begin{aligned}\mathrm{VMP}_{\mathrm{JIRD}_{t-f-g-h-j}} = {} & \left[\sum_{f=1}^{F}\beta_{1f}\right]\left[\frac{\overline{\mathrm{PJI}}}{\overline{\mathrm{RDJI}}}\right]\left[\sum_{g=1}^{G}\gamma_{1g}\right] \\ & \times \left[\sum_{h=1}^{H}\beta_{2h}\right]\left[\sum_{j=1}^{J}\beta_{3j}\right] \\ & \times (P_{\mathrm{W}})_{t-f-g-h-j}(\mathrm{AREA})_{t-f} \qquad (10)\end{aligned}$$

Despite the need to chain the effects, the calculations are straightforward, except that the lags need to be added together as well. Thus, the calculation for returns to PBI R&D in year t–j must be lagged a further i years to allow for the diffusion lag, before discounting, as in Eq. (8), to find the MIRR. For John Innes R&D in year t–f, there is a lag of g years for the knowledge stock, h years before the impact on TPYs and a further j years for the effects to diffuse across the farm population. The slightly lower elasticity gives a MIRR of 17%, which is still very reasonable since it would rise substantially if the other plant breeding institutes were included. Their successes, which are discussed below, suggest that the MIRR to basic science must have been higher than even that for a highly successful applied Institute, such as the PBI. Evenson et al. (1979) similarly found higher returns to basic research for US agriculture.

Thus, the barley and wheat programmes alone are sufficient to give both the PBI and John Innes a minimum social MIRR, on all expenditures, of between 14% and 25%, despite the long lags involved. There are other PBI successes to take into account, which were not negligible. Wheat, barley and potatoes each accounted for about one quarter of the total value of field crop output, between 1950 and 1980, and oats for about 2%. At their peaks, PBI varieties also accounted for over half the oats seed market and over 20% for potatoes. These additions are not of sufficient magnitude to have much effect on the ROR calculations and it seems surprising that major successes should show such modest returns. However, the huge returns, of 70% to 100%, reported by early studies, such as Thirtle and Bottomley (1989), are the result of short series and poor data. With longer series and better data, Khatri and Thirtle (1996) estimated the UK ROR at only 18% for aggregate agricultural output, which is very much in the same range as these results. The limitations of aggregate studies are also clear, in that aggregating across crops would have disguised the differences between barley and wheat.

Fitting standard economic models to the other institutions is not any more feasible than it is for PBI barley. The WPBS accounted for over one third of the oats seed sales and the SPBS for about one third of the seed potato sales. The WPBS concentrated on grasses, so its success with oats is not closely correlated with its R&D expenditures. In fact, there is a more powerful reason for lack of correlation; the WPBS had a negligible share of the acreage, which increased to nearly 50% during World War II, because oats were needed to increase self-sufficiency in food and foreign seeds could no longer be imported. Similarly, the SPBS's success with seed potatoes is not strongly correlated with its R&D, as its interest in seed potatoes began only when management changes took it from concentrating on the needs of crofters in the Western Highlands to seeking commercial success.

Institutional and organizational change clearly matter and another element in the success of public institutes was the Plant Variety Rights (PVR) legislation of 1964. The public varieties began to enjoy patent protection and became increasingly marketable. Indeed, Pray (1995) has shown that the PBI was commercially viable by 1986 and suggests that the government was under-investing in PBI research. The cost of plant breeding at PBI was £2.8 million[5] while the income from sales and royalties attributable to PBI varieties was £5.76 million, after allowing for marketing, distribution and administration.

Over the considerable period covered in this study, the private sector lost its market share to the public institutes, particularly the PBI, which was undoubtedly a highly successful institution, when judged either in social or commercial terms. But the case for public involvement in the allocation of agricultural research resources was already weakened by the commercial viability of plant breeding, following the PVR legislation and deteriorated further as the new technology of genetic mapping increased the possibilities of patenting plant materials.

Hence, the historical success of the PBI is not a strong argument against the strategy of privatization, in that the market failure argument for public intervention had been undermined by institutional and technical change. Nor has the privatized PBI (Plant Breeding International, Cambridge) lost the mixture of breeders and molecular biologists, as they added 25 biotechnologists to their staff, to replace the scientists who remained in the AFRC's Cambridge Laboratory. The resurgence of the private sector, in the shape of multinational companies, such as ICI/Zeneca seeds also suggests that the need for public institutions was already diminishing.

However, the privatization of the PBI is exceptional in one respect, since it did not succeed in reducing public agricultural research. Instead, public sector biotechnology research at the Cambridge Laboratory, in Norwich, increased due to a severe miscalculation on the part of the government. After the government sold the PBI and the National Seed Development Organisation (which marketed public varieties) for £66 million, in 1988, the Charities Commission ruled that the PBI was legally a charitable trust. £38.85 million had to be repaid to the governing body of the PBI and it was used to build and equip the new Norwich laboratory and to hire 25 scientists to add to the staff (Pray, 1995).

7. Conclusion

This paper focuses on the PBI's successes with barley and wheat, first following the history of barley and wheat varieties in the UK from the end of the First World War. In barley, private breeders dominated the market in the 1920s and 1930s, but lost their shares almost entirely to the PBI and foreign varieties by the late 1950s. But, by 1994–1995, the varieties of multinationals are taking market share from the privatized PBI. In wheat, the success of the PBI came later, but was more dramatic, with its market share rising to 90% in the mid 1980s.

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[5] Lazard Brothers, 1987. The PBI and National Seed Development Organisation, Information Memorandum. Unpublished.

The two differ in that the barley technology was on the shelf by 1933, but was not adopted until the late 1940s, when the relative price of meat rose substantially, giving the PBI varieties an economic niche as feed grains. By contrast, the wheat varieties were adopted rapidly. The model fitted for wheat decomposes the effects of basic and applied research and diffusion on farm-level wheat yields. The model is applied to winter wheat in the UK since the Second World War, because of the strong relationship between the PBI's R&D and its share of the winter wheat seed market.

The causal chain model shows the peak lag from basic research to Farm Yields was between 18 to 19 years; one year from expenditures to published output, 13 to 14 from publications to the peak increase in Trial Plot Yields, followed by a peak effect for the diffusion lag after 4 years. For applied research the peak lag was 15 years; 11 years for plant breeding, which fits the pre-biotechnology conventional wisdom closely, and 4 years from the trial plot to the peak effect on FY.

These lags are considerably longer than in aggregate studies, which include extension and other shorter-term expenditures, whereas here basic research is included, but it is highly likely that the length of the series contributes to the result. The short lags in the aggregate studies give high rates of return, which have led to criticism of the methodology. The long lags found in this study reduce the sensitivity of the calculations, but there is no doubt that the rates of return to the (now privatized) UK public-sector plant breeding programmes were high by any normal standards. The returns to basic and applied research are estimated to be between 14% and 25% for wheat and barley, even if the two programmes had to carry the full cost of the PBI and the wheat gains alone cover the full cost of the JII since World War 2.

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