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# The Productivity of UK Universities


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# The Productivity of UK Universities*

by

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## *1. Introduction*

There is increasing recognition in the UK and other OECD countries of the importance of scientific research in providing the foundations for both innovation and competitiveness. This has resulted in increased public funding for research in the UK and elsewhere. At the same time, there is a lack of systematic evidence on how such investments can lead to increasing levels of scientific output and, ultimately, to better economic performance. Much of the available literature concentrates on the effects of public funding of basic research on either firms' innovative activities (see among others COHEN, NELSON AND WALSH [2002]; KLEVORICK, LEVIN, NELSON AND WINTER [1995]; JAFFE [1989]; NARIN, HAMILTON AND OLIVASTRO [1997]) or firm performance (Adams [1990]), bypassing the question of how to measure scientific output. The reasons for this are the difficulty of identifying a stable causal relationship between the resources spent on the science budget and 'intermediate' scientific outputs. This difficulty originates from the dynamic nature of this relationship. There is a persistent and therefore recursive feedback between inputs and outputs, which is exacerbated by lack of appropriate information for analysis. Among the few studies that have attempted to address the problem, are ADAMS AND GRILICHES [1996] and JOHNES AND JOHNES [1995]. This study is based on and further develops Adams and Griliches's methodology.

The national science budget comes from several sources. For example, the UK Higher Education sector received a total of £4,035 millions for research and development in 2001, financed by the Office of Science and Technology (OST) via the research councils (£942), Higher Education Funding Councils (HEFC) (£1,474), other UK sources such as direct Government (£238), Higher Education Institutions (£166), non-profit organisations (£660) and business enterprises (£250), and funding from other countries or supranational institutions (£304). These contributions are allocated within the system according to scientific field and research institution, to provide the resources needed for research.

The scientific process produces several research outputs that can be classified into three broadly defined categories: (1) new knowledge; (2) highly qualified human resources; and (3) new technologies. This paper focuses on the determinants of the first two types of research output, which are the most closely related to the science research budget. There are no direct measures of new knowledge, but several proxies have been applied in previous studies. The two that we use in our study, which are also the most commonly used measures are publications and citations. These are incomplete proxies for the production of new knowledge and have several

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shortcomings (GEUNA [1999]). Highly qualified human resources have been proxied by the total number of graduate students that have completed their studies.

In this paper we focus on the determinants of university research output (as measured by publications, citations and numbers of graduate students) in the UK. We use an original dataset that includes information for the 52 'old' UK universities across 29 scientific fields for a period of 18 years (1984/85-2001/02). The paper do not aim to produce exact indicators of the dynamics of the science system, on the basis of which, to draw strong policy conclusions. and we fully acknowledge the limitations of the input-output data we use.

The paper is structured as follows. In Section 2 we present the methodology and the data sources; we depart from the traditional static knowledge production function model to estimate different dynamic panel data specifications. In Section 3 we present and discuss the results of the estimations. In Section 4 we use the residuals of our fitted knowledge production functions to evaluate the evolution of UK scientific productivity. Finally, in the conclusion we discuss the limitations of this study and suggest possible further developments.

*2. Methodology and data sources*

Our methodological approach develops the standard knowledge production function model of ADAMS AND GRILICHES [1996]. They use the expression:

$$y_{it} = \alpha_i + \beta W(r)_{it} + \gamma_i X_{it} + u_{it}, \quad i = 1,......N \quad (1)$$

where $y_{it}$ is the (log) output of the research 'intermediate' output (papers and citations) by field $i$ and time $t$. $W(r)_{it}$ is (the log of) a distributed lagged function of real past R&D expenditure and $X_{it}$ is a vector of the control variables. The main focus of this analysis is on $\beta$, the elasticity of the research output with respect to research input and the measure of local returns to scale in research. Diminishing (constant or increasing) returns predominate when $\beta<(\geq 1)$.

In order to build a science capital stock we need: the time length over which the past investments in university R&D are considered to be relevant for the current research; and a weighing scheme to account for past university R&D. This is where our methodology departs from ADAMS AND GRILICHES [1996]. While they present the results for three and five year distributed lags of R&D, where the weighting pattern is completely ad hoc, we search for a lag structure, and develop a procedure to estimate a flexible and a 'data driven' lag structure.

There are two dominant models. First, the Autoregressive Distributed Lag (ADL) model, which assumes a very flexible and unrestricted relationship between (log) R&D inputs and outputs, but at the cost of estimating a large number of parameters (see for example, GUELLEC AND VAN POTTELSBERGHE [2001] and KLETTE AND JOHANSEN [2000]). Second the Polynomial Distributed Lag (PDL) or Almon Model, which specifies the weights as polynomial functions of a particular estimated degree (Crespi and Geuna [2004]). These log linear models imply a strong *complementarity* between the knowledge imputes.[1] In other words, the greater the initial knowledge, the greater will be the amount of knowledge obtained from a given amount of R&D. The more knowledge that is produced, the more it can be recombined to produce new knowledge. Formally we will assume that:

$$K_{it} = \prod_{j=0}^{J} R_{it-j}^{w_j} \quad (2)$$

In this paper we present the results of the PDL Model; we used the ADL model in another paper and obtained consistent results. Let us now define the following 'finite' distributed lag model:

$$y_{it} = \alpha_i + \sum_{j=0}^{q} \beta_j r_{it-j} + \gamma_i X_{it} + u_{it}, \quad i = 1,......N \quad (3)$$

Although a model like (3) in theory can be estimated in a straightforward manner, there is the potential problem of very long lags in which case the multicolinearity is likely to become quite severe. In such cases it is common to impose some structure on the lag distribution, reducing the number of parameters in the model. It is in this context that the PDL model can be useful. The approach is based on the assumption that the true distribution of the lag coefficients can be very well approximated for by a polynomial of a fairly low order:

$$\beta_j = \delta_0 + \delta_1 j + \delta_2 j^2 + .......+ \delta_p j^p, \quad j = 0,......q > p \quad (4)$$

The order of the polynomial, *p,* is usually taken to be quite low, rarely exceeding 3 or 4. By inserting (4) into (3), one can estimate a transformed model where the estimated coefficients are the deltas that can be put back into (4) in order to recover the original weights. In addition to the $p+1$ parameters of the polynomial, there are two unknowns to be determined: the length of the lag structure, *q*, and the degree of the polynomial, *p*. Here we follow the non-standard procedure of setting the length of the lags using a priori information and then searching for the degree of the polynomial function.

The usual standard procedure is to use the same dataset first to search for the optimum time lag (using some information criteria) and then, taking the best lagging as true, to search for the optimum polynomial function. However, this sequential search approach carries the problem that unless the test statistics are overwhelming, the true significance levels in the tests remain to be derived, and the true distribution of the resulting estimator is unknown. Following the evidence in CRESPI AND GEUNA [2004] for a large set of OECD countries, we set a lag length of 6 years for publications and research students, and 7 years for citations.

Assuming that we know the right lag length we proceed by looking for the right polynomial function. We start by using a 5th degree function and proceed by testing sequential unit reductions in the degree. It is important to note that in order to retain

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[1] By complementarity we mean that marginal productivity of current R&D investment tends to zero if past R&D investment also tends to zero. This assumption is particularly apt in the case of science where we 'stand on the shoulders of giants' to build new knowledge.

the appropriate significance level in each step we used a very low individual significance level. The PDL model also implies a set of constraints on the unrestricted model (without a specified functional form for the lags). For example, if the known lag length is 6 and we use a 3rd degree polynomial function, we are implicitly imposing three constraints. In addition, we have endpoint constraints, which allow the lag distribution to be 'tied down' at its extremes. These endpoint constraints capture the idea that there is no effect of R&D on the research outputs *before* the current period and also that there is no effect from the research inputs after the maximum lag. That is, we need to impose:

$$\beta_{-1} = 0 \qquad and \quad \beta_{q+1} = 0 \qquad (5)$$

In total we have five constraints. One way to validate the PDL model is to test whether these constraints are valid, which can be done by using a simple Chi2 test.

Finally, the PDL model also requires exogeneity of R&D. We carried out a Bivariate Granger Causality test. Following ROUVINEN [2002], we implemented the test using a Dynamic Panel Data in Difference (DPD-DIF) model, where the first differences of the dependent variables are regressed on lags of the first differences of the dependent and independent variables. The findings (not reported here for reasons of space, but available from the authors) would suggest that there is a two-way causality between R&D, and publications and citations. This may result in a biased estimation of the elasticity coefficients. Given the problems with available data, and the experimental nature of our work, we acknowledge that our estimations will be biased, and, taking a conservative approach, we nevertheless decided to use the PDL model because it allows us to use the level variables and therefore to maintain a high level of information, which is crucial in the case of variables such as ours which are very noisy.

*2.1 Data sources*

To estimate the model we used the SPRU SCIENCE FIELD database.[2] The dataset includes information on 52 old universities covering 29 scientific fields, over an 18 year period 1984/85 to 2001/02.[3] The 52 old universities considered provide a good representation of the scientific research carried out in UK universities; in 2001/02 Research Grant and Contract income for these universities accounted for 87% of total UK Research Grant and Contract funding. The dataset has four variables (not including institution and field ids): information on Total Research Grant and Contract income;[4] number of publications; number of citations;[5] and total number of graduate students.

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[2] A detailed description of the procedure used for the development and content of the datasets can be found in CRESPI AND GEUNA [2004].

[3] The 52 old universities does not include the Open University, Cranfield University, the independent University of Buckingham (not in University Statistical Record statistics) or Lancaster University (not in the Higher Education Statistical Agency statistics). Due to problems with the archiving of the University Statistical Record data, London University data are the sum of all its colleges. Not all the universities are active in every scientific field, every year.

[4] Total Research Grant and Contract income include all direct research funding received from the research councils, industry, the EC, foundations, etc. Total Research Grant and Contract income accounted for 38% of total research income in 1988/89 increasing to about 60% in 2000/01 (http://www.ost.gov.uk/setstats/5/t5_1.htm; accessed 26/1/2006). We were not able to obtain Total

In the following sections we present the results of the field level estimates of the science production function for publications, citations, and graduate students. Because information about publications and citations is only available at field level, we cannot estimate a knowledge production function for each of the 29 fields. We need to aggregate the micro fields into more broadly defined categories by mapping the 29 fields into the 4 broad categories in the OECD statistics. The four-macro fields analysed were: natural sciences; engineering; medical sciences; and social sciences.

Table 1: UK Research Outputs

| | Publications | | | | Citations | | | | Graduate Students | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | NS | ENG | MS | SS | NS | ENG | MS | SS | NS | ENG | MS | SS |
| 1984 | 43.3% | 13.8% | 32.8% | 10.1% | 44.7% | 7.5% | 41.1% | 6.7% | 43.6% | 18.8% | 9.3% | 28.3% |
| 1985 | 42.1% | 13.8% | 33.9% | 10.2% | 42.7% | 7.6% | 42.4% | 7.2% | 43.2% | 19.5% | 9.2% | 28.1% |
| 1986 | 42.2% | 14.0% | 33.9% | 9.9% | 42.2% | 7.4% | 43.2% | 7.2% | 43.5% | 20.1% | 8.7% | 27.7% |
| 1987 | 41.7% | 14.0% | 34.5% | 9.8% | 41.9% | 7.8% | 42.9% | 7.4% | 43.7% | 20.5% | 9.3% | 26.4% |
| 1988 | 41.3% | 14.9% | 34.4% | 9.3% | 41.8% | 8.0% | 43.2% | 7.0% | 44.3% | 20.3% | 8.9% | 26.6% |
| 1989 | 40.6% | 14.1% | 35.9% | 9.4% | 40.2% | 7.4% | 45.2% | 7.2% | 44.7% | 19.3% | 8.9% | 27.2% |
| 1990 | 41.1% | 14.9% | 35.0% | 9.1% | 41.1% | 8.1% | 44.2% | 6.6% | 43.5% | 19.0% | 9.2% | 28.3% |
| 1991 | 40.6% | 15.4% | 34.9% | 9.1% | 41.0% | 7.9% | 44.6% | 6.5% | 43.4% | 18.8% | 9.6% | 28.2% |
| 1992 | 40.5% | 16.0% | 34.3% | 9.1% | 40.9% | 8.2% | 44.6% | 6.3% | 42.6% | 19.1% | 9.6% | 28.8% |
| 1993 | 41.1% | 15.6% | 34.6% | 8.7% | 41.1% | 8.0% | 44.7% | 6.2% | 40.7% | 19.0% | 10.1% | 30.1% |
| 1994 | 41.0% | 16.5% | 33.7% | 8.8% | 40.9% | 8.1% | 44.6% | 6.4% | 38.8% | 19.1% | 10.0% | 32.1% |
| 1995 | 41.2% | 16.3% | 33.0% | 9.5% | 42.1% | 7.9% | 43.9% | 6.2% | 37.5% | 18.8% | 10.3% | 33.3% |
| 1996 | 40.8% | 16.5% | 32.9% | 9.8% | 41.6% | 8.5% | 43.2% | 6.7% | 35.9% | 17.9% | 12.0% | 34.2% |
| 1997 | 41.2% | 15.8% | 33.0% | 10.0% | 41.7% | 7.9% | 43.8% | 6.5% | 35.1% | 17.4% | 12.3% | 35.3% |
| 1998 | 41.1% | 16.1% | 33.0% | 9.9% | 42.7% | 8.2% | 42.6% | 6.5% | 34.7% | 16.9% | 13.1% | 35.3% |
| 1999 | 41.1% | 16.5% | 32.5% | 9.8% | 42.2% | 8.4% | 43.0% | 6.3% | 34.1% | 16.9% | 13.4% | 35.6% |
| 2000 | 40.6% | 16.0% | 32.8% | 10.6% | 42.3% | 8.2% | 43.4% | 6.1% | 33.5% | 17.3% | 13.4% | 35.8% |
| 2001 | 40.9% | 16.1% | 32.5% | 10.5% | 43.6% | 7.9% | 42.6% | 5.8% | 32.9% | 17.7% | 13.3% | 36.0% |

Source: Evidence

NS: Natural Sciences; ENG: Engineering; MS: Medical Sciences, SS: Social Sciences.

Table 1 summarises the main research outputs used in this section. Across the entire period, there is a remarkable stability in the distribution of research outputs by field. Broadly speaking, Natural Sciences and Medical Sciences together account for 75% and 85% of total publications and citations respectively, in the UK. The remaining percentage is split between Engineering (15% and 8% respectively) and Social Sciences (10% and 6% respectively). The picture changes dramatically when we focus on graduate student research output where the importance of Natural Sciences declines to slightly over 30% at the end of the period, while Medical Sciences increases from 9% to 13%. Taken together, these two macro fields have a much lower output share (45% at the end of the period). Engineering remains stable at around 18% for the period, while Social Sciences shows a systematic growth from 28%, to 36% towards the end of the period.

Research Income broken down by scientific field because this breakdown of HEFC funding by institution and subject area for the whole period was not available.

[5] The source of publication and citation numbers is the Thomson ISI(R) 'National Science Indicators' (2002) database.

In order to account for the 'truncation problem' in the citations for the most recent years, the citations variable was adjusted.[6] One way of controlling for truncation is to use what HALL, JAFFE AND TRAJTENBERG [2001] describe as the fixed effect approach. This involves scaling citations counts by dividing them by the average citation count for a group of publications to which the publication of interest belongs. Thus, a publication that received say 11 citations and belongs to a group in which the average publication received 10 citations, is equivalent to a publication that received 22 citations, and belongs to a group where the average number of citations is 20. The groups were defined in terms of scientific field and year and the scaling index was computed using the ISI dataset at world level.

On the basis of these data sources we:

- Estimate the science production function for the OECD macro fields (natural sciences, engineering, medical sciences, and social sciences) using information on 29 science fields available for the UK;
- Examine the changes in productivity growth across fields.

*3 The UK knowledge production function estimates*

In this section we present the results of the field level estimates of the science production function for publications, citations, and graduate students.[7] The four macro fields analysed are: natural sciences, engineering, medical sciences, and social sciences. For each of these macro fields, the aim was to estimate a science production function as follows:

$$y_{it}^{F} = \alpha_{i}^{F} + \beta^{F} W(r)_{it}^{F} + \gamma^{F} X_{it}^{F} + u_{it}^{F}, \quad i = 1,.....N; F = 1,...J \quad (6)$$

where $y_{it}$ is the (log) output of the research 'intermediate' output (papers, citations, and graduate students) by scientific micro field $i$ (we have 29 scientific micro fields classified into the 4 broad fields listed above) and time $t$ (period 1984-2001). $W(r)_{it}$ is (the log of) a distributed lagged function of real past Research Grants and Contract income by scientific micro fields and $X_{it}$ is a vector of the control variables described below. As explained above, a 6-year lag for publications and graduate students, and a 7-year lag for citations were applied; then, conditional on them, we tested the shape of the lag function using 4, 3 and 2 degree polynomial functions. In all cases we could not reject that the 3rd degree polynomial function was the correct one. Also in all cases we tested an unconstrained model and could not reject the constrained model as valid.

The vector $X_{it}$ refers to a series of control variables included to assess two important phenomena:

- first, we want to control for the way in which time is allocated by the researchers. One of the most important decisions regarding time for many (but not all) university researchers is how it is allocated between research and

[6] The citation count is affected by the time span allowed for the papers to be cited: for example, papers published in 2000 can receive citations in our data only from papers published in the period 2000-2001; they will be cited by papers in subsequent years, but we do not observe them.

[7] A national level science production function model was statistically rejected in favour of four very broadly defined macro-fields.

(undergraduate) teaching activities. Because we have information about the number of undergraduate students by field and year, we can control for the impact on research output of teaching intensity in the different fields;

- second, research output can be affected by factors specific to the university (Geuna [1999]). We test for three effects: a) localisation (London based universities); b) research propensity (Russell group universities versus Group 1994 universities); and c) reputation (when the university was founded).

The control variables are as follows:

- *Teaching Load*: is the ratio of undergraduate students to total staff, computed by field and year.[8]
- *London*: refers to the proportion of research income in each field that is invested in universities located in London.
- *Russell*: refers to the proportion of research income in each field that is spent in universities affiliated to the Russell Group (self-selected group of research-led universities).
- *Group 94*: is the proportion of research income in each field that is spent in universities that belong to the 1994 Group (self-selected group of research-led universities that are, on average, smaller than the Russell Group, more oriented to teaching, and with less prestigious research reputations).
- *Medieval Universities*: is the proportion of research income in each field allocated to universities founded before the 18$^{th}$ century.
- *19$^{th}$ Century Universities*: is the proportion of research income in each field allocated to universities founded in the 19$^{th}$ century.
- *20$^{th}$ Century Universities*: is the proportion of research income in each field allocated to universities founded in the first half of the last century.
- *Post WWII universities*: is the proportion of research income in each field spent in universities founded after the Second World War, mostly redbrick universities.

The coefficients of these control variables to some extent, capture the differences in research productivity of the various institutions. The available literature on university research production allows us to hypothesise a negative coefficient for the undergraduate teaching variable: we can expect a negative impact on research production due to the allocation of more time to undergraduate teaching activities. The localisation of universities in the London area should create positive externalities for research, which increases the productivity of those institutions located in London. We expect a positive value for the variable London. With regard to the other control variables no clear a priori expectation can be formulated; to our knowledge this is the first study that has attempted to evaluate these effects. A possible hypothesis is that those universities that are more research-led and more prestigious tend to assign more importance, and therefore more support, to research, which should translate into higher research productivity.

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[8] Information on teaching intensity ratio is only available from 1993. As the estimation sample starts in 1989, we had to reconstruct the ‘missing’ period. The best imputing mechanism was using university level linear interpolation, which respects the heterogeneity across universities and fields.

We estimate the model for the three research outputs: publications; citations; and number of graduate students.

*3.1 Publications*

We first show the pattern of weights and then proceed to the results of the model. As is clear from Figure 3.1, a first important result of our estimation is that the lag structures are significantly different across fields. Social Sciences has a relatively important impact in the short run (during the first two years) but the effects diminish over time; the situation in the Natural and Medical Sciences is the reverse, the bulk of the impact being concentrated towards the end of the lag span. Finally, in the case of Engineering we have a clear parabolic function, which suggests a concentration of impact towards the middle of the time period. These differences in the weighting function are very important because they point to a differential impact of a given increase in the science budget over time. The research output generated by Social Sciences is much more immediate than in the other sciences, leading to an increase in the share of Socials Sciences in total publications in the short run. This situation is reversed over time in favour of the Natural and Medical Sciences.

{FIGURE 3.1 ABOUT HERE}

Table 2: UK Levels Estimates, Publications
(Method: field fixed effect)

| | Natural Sciences | Engineering | Medical Sciences | Social Sciences |
|---|---|---|---|---|
| R&D | 0.208 | 0.216 | 0.461 | 0.340 |
| | 0.112* | 0.132* | 0.145*** | 0.086*** |
| Year | 0.014 | 0.036 | 0.011 | 0.033 |
| | 0.007* | 0.009*** | 0.009 | 0.006*** |
| Undergraduate Teaching | -0.032 | -0.014 | -0.052 | -0.017 |
| | 0.010*** | 0.014 | 0.009*** | 0.007** |
| London | 0.001 | -0.012 | 0.003 | -0.001 |
| | 0.003 | 0.003 | 0.004 | 0.005* |
| Group94 | 0.001 | 0.004 | 0.003 | -0.008 |
| | 0.004 | 0.005** | 0.003* | 0.005 |
| Russell | 0.004 | -0.004 | 0.006 | 0.000 |
| | 0.003 | 0.003 | 0.003 | 0.005 |
| Medieval | 0.002 | 0.005 | -0.017 | 0.013 |
| | 0.005 | 0.004 | 0.007** | 0.004*** |
| $19^{th}$ Century | 0.001 | 0.007 | -0.008 | 0.009 |
| | 0.004 | 0.003** | 0.004* | 0.004** |
| $20^{th}$ Century | 0.008 | 0.005 | -0.001 | 0.018 |
| | 0.005 | 0.007 | 0.004 | 0.012 |
| Constant | -21.630 | -67.578 | -19.889 | -64.677 |
| | 12.254* | 15.157*** | 16.129 | 11.184*** |
| Observations | 108 | 84 | 72 | 84 |
| R-squared | 0.83 | 0.78 | 0.88 | 0.86 |
| Chi(2) | 2.97 | 7.10 | 7.75 | 7.44 |
| P>Chi(2) | 0.71 | 0.21 | 0.17 | 0.19 |
| 50% Quartile Lag (years) | 3.8 | 2.1 | 4.0 | 1.1 |
| 90% Quartile Lag (years) | 5.5 | 4.6 | 5.6 | 3.1 |

Robust standard errors reported below each coefficient. Within R-squared reported.
(*) significant at 10%; (**) significant at 5%; (***) significant at 1%

Table 2 presents the results from using the described weighting pattern to compute the sector knowledge stock and to estimate model (6). The first interesting result is that the long run elasticity between knowledge stock and publications varies widely across broadly defined fields. The highest elasticity is found in Medical Sciences (0.46) and the lowest in Natural Sciences (0.20). In all four cases elasticities are significant. The year effect, which captures the long run trend in scientific opportunities affecting research output, is always positive. It is important to note that as this model does not include a specific variable for spillovers from abroad (an international co-authorship matrix in each science field would be needed) the time trend also captures international spillover effects. The year trend value is highest for Engineering Sciences, and smallest for Medical Sciences.

In terms of the impact distribution of changes in the research budget, the last two rows of Table 2 show the median lag (the year that accumulated at least 50% of the impact) and the 90$^{th}$ percentile lag. Consistent with the weight patterns, the most immediate impact is in Social Sciences where 90% of the effect is observed after 3 years, compared to Medical Sciences where it is 5.5 years before 90% of the effect is seen.

We obtained statistically significant and important coefficients for some of the control variables. First, the variable capturing teaching load is statistically significant and important for all fields except Engineering Sciences. The coefficient is always negative, confirming that large undergraduate teaching loads have a disruptive effect on scientific production. The biggest effect is in Medical Sciences. In this case, an increase of 1 additional undergraduate student per research staff member has the effect of reducing research output by about 5%. Second, and rather surprisingly,, a higher allocation of funds to London based universities results in a slightly less productive system in Social Sciences. Third, also contrary to expectation, we found some evidence to support the view that a bigger allocation of funds to the 1994 Group universities would result in an overall higher research output in the Engineering and Medical Sciences; no significant effect was identified for the Russell Group universities.[9] Fourth, a larger share of funds to the Medieval universities was shown to result in a more productive system in Social Sciences, but a negative impact on Medical Sciences. A larger share of funds to the 19$^{th}$ Century universities had a positive effect on the Engineering and Social Sciences research output, and a negative impact on Medical Sciences. The comparator groups for university history is the group of universities founded after WWII. Finally, the tests for validity of the constraints were never rejected.

*3.2 Citations*

Citation output was analysed following the procedure used for publications. Figure 3.2 shows the pattern of weights for the different disciplines. The results appear similar to those for publications. The citation output tends to respond more quickly to an increase in R&D investment in Social Sciences than the other scientific fields. Medical Sciences shows its largest research impact only at the end of the time period, while the polarisation is less strong for the Natural Sciences and Engineering. The main difference from the publication lag structure results is the very similar pattern

[9] The higher output could be due to two phenomena: higher productivity of the 1994 Group universities, or the competition effect from the other universities which received less funds. University level micro data would be needed to disentangle these two effects. This reasoning applies to the other resource allocation control variables.

for Engineering and Natural Sciences: Engineering Sciences has a less symmetric profile and behaves much more like Natural Sciences.

{FIGURE 3.2 ABOUT HERE}

Table 3 presents the results for the estimation of model (5) in the case of citations output. In terms of long run science budget elasticity the results are very similar to the results for publications. The highest elasticity is found in Medical Sciences (0.61), while the lowest is in Engineering Sciences (0.15), which is non-significant. The time trend variable is always positive and significant in three of the fields, once again pointing to an increase in scientific opportunities and the existence of international spillovers. Regarding the impact distribution of changes in the research budget, the earliest impact is in Social Sciences where 90% of the effect is observed after about 4 years, while in Medical Sciences 90% of the effect is achieved only after 6 years.

Table 3: UK Levels Estimates, Citations
(Method: field fixed effect)

| | Natural Sciences | Engineering | Medical Sciences | Social Sciences |
|---|---|---|---|---|
| R&D | 0.212 | 0.146 | 0.617 | 0.353 |
| | 0.123* | 0.196 | 0.160*** | 0.095*** |
| Year | 0.014 | 0.037 | 0.005 | 0.032 |
| | 0.008* | 0.009*** | 0.011 | 0.007*** |
| Undergraduate Teaching | -0.031 | -0.018 | -0.059 | -0.016 |
| | 0.010*** | 0.014 | 0.012*** | 0.007** |
| London | 0.001 | -0.011 | 0.007 | -0.008 |
| | 0.003 | 0.003 | 0.003 | 0.005 |
| Group94 | 0.001 | 0.004 | 0.003 | 0.001 |
| | 0.004 | 0.003 | 0.003 | 0.005 |
| Russell | 0.004 | -0.004 | 0.004 | 0.000 |
| | 0.003 | 0.005** | 0.004* | 0.005 |
| Medieval | 0.002 | 0.005 | -0.018 | 0.013 |
| | 0.005 | 0.005 | 0.007*** | 0.005*** |
| $19^{th}$ Century | 0.001 | 0.006 | -0.008 | 0.009 |
| | 0.004 | 0.003** | 0.004* | 0.004** |
| $20^{th}$ Century | 0.008 | 0.004 | 0.002 | 0.018 |
| | 0.005 | 0.007 | 0.006 | 0.012 |
| Constant | -22.493 | -67.690 | -10.691 | -63.943 |
| | 12.946* | 16.240*** | 18.718 | 12.118*** |
| Observations | 108 | 84 | 66 | 84 |
| R-squared | 0.68 | 0.77 | 0.84 | 0.67 |
| Chi(2) | 1.398 | 2.760 | 8.635 | 7.160 |
| P>Chi(2) | 0.966 | 0.838 | 0.195 | 0.306 |
| 50% Quartile Lag (years) | 4.4 | 3.3 | 4.3 | 1.6 |
| 90% Quartile Lag (years) | 5.5 | 5.3 | 6.0 | 3.9 |

Robust standard errors reported below each coefficient. Within R-squared reported.
(*) significant at 10%; (**) significant at 5%; (***) significant at 1%

Regarding the remaining control variables, the results tend to be consistent with those for publications, with the exception of the control variable for the Russell Group universities: a larger allocation to 1994 Group universities does not have a positive effect on the system output, while a higher share of funds to Russell Group universities has a positive impact on citations in Medical Sciences, but a negative impact in Engineering Sciences. The teaching variable is again negative, with the highest absolute value in Medical Sciences. A bigger allocation to London based universities does not provide any positive advantage. Larger proportions of direct funding to Medieval universities result in a higher citations output in Social Sciences and lower returns in Medical Sciences, similar to the 19$^{th}$ Century universities, with the adjunct of a positive impact for Engineering. Finally, as before, the constraints implied by the model were not rejected.

{FIGURE 3.3 ABOUT HERE}

*3.3 Graduate students*

The third science output we examined at the field level for the UK is the 'production' of graduate students. Figure 3.3 shows the lag structure. The most interesting result of this analysis is that the patterns appear quite different from the patterns for publications and citations. This result might be because graduate students are a research output of a completely different nature to publications and citations. In the case of graduate students, Medical Sciences, Engineering and Natural Sciences show the strongest impact quite quickly (in the first three years), while the impact in Social Sciences does not become evident until towards the end of the time frame. We do not have a definitive explanation for this result, but we incline to the view that the combination of a different mix of graduate courses (MSc, Mphil and PhD) across the different fields might be generating these sorts of differential impacts.

Table 4: UK Levels Estimates, Graduate Students
(Method: field fixed effect)

| | Natural Sciences | Engineering | Medical Sciences | Social Sciences |
|---|---|---|---|---|
| R&D | 0.542 | 0.107 | 0.656 | 0.214 |
| | 0.200*** | 0.173 | 0.158*** | 0.091** |
| year | -0.024 | 0.027 | 0.044 | 0.064 |
| | 0.011** | 0.009*** | 0.011*** | 0.007*** |
| Undergraduate Teaching | -0.062 | -0.044 | -0.024 | 0.015 |
| | 0.015*** | 0.020** | 0.010** | 0.006*** |
| London | 0.002 | 0.009 | -0.01 | -0.005 |
| | 0.004 | 0.004 | 0.004 | 0.003 |
| Group94 | 0.003 | 0.003 | 0.005 | -0.005 |
| | 0.006 | 0.005* | 0.006 | 0.002 |
| Russell | 0.005 | -0.003 | -0.009 | 0.003 |
| | 0.004 | 0.005 | 0.006 | 0.002* |
| Medieval | -0.015 | 0.004 | 0.028 | 0.006 |
| | 0.009 | 0.005 | 0.014* | 0.004* |
| 19$^{th}$ Century | -0.014 | -0.005 | 0.017 | 0.003 |
| | 0.007** | 0.004 | 0.008** | 0.004 |
| 20$^{th}$ Century | -0.014 | 0.008 | 0.002 | 0.015 |
| | 0.008* | 0.007 | 0.003 | 0.007** |
| Constant | 47.113 | -48.338 | -93.097 | -124.08 |
| | 18.987** | 16.708*** | 19.154*** | 13.174*** |
| Observations | 99 | 77 | 66 | 77 |
| R-squared | 0.70 | 0.65 | 0.87 | 0.92 |
| Chi(2) | 3.005 | 0.635 | 10.952 | 9.803 |
| P>Chi(2) | 0.699 | 0.986 | 0.052 | 0.081 |
| 50% Quartile Lag (years) | 1.3 | 0.8 | 1.1 | 3.8 |
| 90% Quartile Lag (years) | 3.5 | 2.8 | 3.1 | 5.3 |

Robust standard errors reported below each coefficient. Within R-squared reported.
(*) significant at 10%; (**) significant at 5%; (***) significant at 1%

Table 4 shows the results of estimating model (6) using field fixed effects. The largest elasticities regarding this type of research output is found in the Natural and Medical Sciences with values of 0.54 and 0.65 respectively. The corresponding elasticities for Social Sciences (0.21) and Engineering (0.11 and non-significant), are much lower. The time trend had a positive coefficient in all fields except Natural Sciences. This points to an increase in productivity in Social and Medical Sciences and Engineering regarding the 'production' of graduate students. In terms of the impact distribution of changes in the research budget, the most immediate impact is in Engineering, where 90% of the effect is observed after about 3 years, while the most delayed impact is in Social Sciences where it takes 5.3 years for 90% of the effect to be felt.

Regarding the remaining control variables there are some interesting results. First, the undergraduate teaching variable is negative in Natural Science, Medical Sciences and Engineering, pointing to the fact that in these fields an increase in the undergraduate teaching load negatively affects the time allocated to supervising and guiding graduate students. In contrast, in Social Sciences we have a positive impact from undergraduate teaching towards graduate teaching, pointing to an apparently different nature of graduate studies in this field, a possibility that requires much more analysis for it to be confirmed. Second, as before, there was no evidence of a positive localisation effect for a higher allocation of grants and contracts to London based universities. Third, a bigger allocation of funds to the universities belonging to the 1994 Group had a positive premium in Engineering, while for those in the Russell Group the biggest premium was in Social Sciences. Fourth, in terms of age, a higher share of funds to Medieval universities has a positive effect in Social and Medical Sciences, while more funding to the $19^{th}$ Century universities induces an increase in the university system output in Medical Sciences, but and a decrease in Natural Sciences. This last result also applies to the $20^{th}$ Century universities, which also showed a positive premium in Social Sciences. The comparator group, as in the previous two estimations, was the category of the Post WWII universities. Finally, as before, in all the models the constraints were not rejected.

Field level estimates provide us with an interesting set of results. Most of these are novel to the literature on the economics of science and, thus should be seen as preliminary and exploratory, to be confirmed by further analyses. First, in the case of Medical Science, Social Sciences, and Natural Sciences we can identify positive and significant returns for publications, citations, and graduate students from investment in higher education R&D. Although positive, the effect for Engineering is only significant in the case of publications, pointing to the fact that the research output from this scientific field is better captured by measures other than citations and research students. Second, the four scientific fields tend to have different lag structures. this is particularly noticeable in the case of Social Sciences. While investment in R&D in Social Sciences affects publications and citations more immediately than in the other three fields, in the case of gradate students most of the returns to Research Grant and Contract funding are concentrated at the end of the period. Third, we found strong evidence that a high undergraduate teaching load negatively affects the research outputs of UK universities. Only in the case of graduate students in Social Sciences did we find a positive effect. Fourth, we constructed a set of control variables to assess the importance of allocation of grants and contracts to different subgroups of universities (university specific effects). Some of these were significant and important, pointing to the fact that different allocations of funds to universities result in higher or lower university system scientific production. The higher or lower output may be due to higher productivity in the institutions that received more grants and contracts or a competition effect from the universities that received less funds. Micro data at the level of the university would be needed to identify which of the two effects is dominant.

*4 The UK knowledge productivity analysis*

This section focuses on the efficiency with which the domestic stock of knowledge (Science Budget and other grants and contracts) is applied in order to generate the different research outputs. Has this efficiency grown over time or has it declined across disciplines? Building on the results in section 3 we computed field specific total factor productivities (TFPs). These TFPs capture the evolution of the scientific opportunities in each field, and also the effects of changes in organisational practices, resources allocation, and management.

For each (macro field) we computed the residual of the knowledge production function (6) as:

$$tfp_{it}^{F} = y_{it}^{F} - \beta^{F} W(r)_{it}^{F}, \quad i = 1,.....N; F = 1,...J \quad (6)$$

where $tfp_{it}$ is the knowledge production function (semi) residual after controlling for changes in $W(r)_{it}$, the distributed lagged function of real past R&D expenditures. In order to compute (6) we first need an estimation of the elasticity coefficients by field (the $\beta$s). We use the field level results shown in Tables 2 to 4. Given the lags used in the construction of $W(r)_{it}$ we can only focus on productivity evolution during the 1990s.

Figures 4.1, 4.2 and 4.3 show the evolution of the TFP index by field over time for each of the research outputs. Two clear patterns emerge. In all macro fields and research outputs there is an upward trend in the productivity indices, suggesting that there is a clear improvement in the efficiency and technological opportunities of the system. In all four major scientific fields and for the three traditional outputs of scientific research, the productivity of UK science has increased along the 1990s. However, from the mid 1990s, in all the macro fields, there has been a marked slowdown in productivity growth rates as highlighted by the less steep slopes of the productivity indices at the right of the figures.

{FIGURE 4.1, 4.2 AND 4.3 ABOUT HERE}

Across the whole period the TFP growth rate in the case of publications has fluctuated between 1.2% and 2.4%, with the lowest value in Natural Sciences and the highest in Social Sciences. Taking the cut-off point of 1996 (chosen to coincide with the 1996 RAE), the average TFP growth rates during the first half of the 1990s was compared to the same indicator for the 1990s to 2001. The data show a remarkable slowdown in productivity, TFP productivity growth rates declined by more than 50% in Natural Sciences, Engineering (the largest decrease) and Social Sciences, but by 'only' 22% in Medical Sciences. Numbers of citations show a similar profile. The highest growth rate is in Engineering Sciences (2.4%) and the lowest in Medical Sciences (0.8%).

There is also a clear slowdown in productivity growth rates, but the degree of the decline is even greater than in publications. Finally, the results for graduate students are similar to those for citations with the exception that the highest growth rate occurs in Medical Sciences. The slowdown in the second half of the 1990s is also remarkable: in Engineering and Natural Sciences TFP growth rates halved, while in Social and Medical Sciences TFP growth rates are 60% of their value in previous period.

It is important to note that the productivity slowdown is not an artefact of the increased spending in UK science. The real increase in the science and engineering R&D spend in the UK started in 2000-01. In our model the impact on research outputs of an increase of about 7% in 2000-01 is spread across the succeeding 6/7 years; the weight for the first year is small in the case of publications and citations (lower than 10% for all except the Social Sciences) and about 25% in the case of Graduate Students (again excepting Social Sciences for which it is near zero). A significant increase in R&D spending in a particular year can negatively affect the overall productivity of the system in that year if a simple productivity measure based on the ratio between that year's inputs and outputs is considered. Our measure of productivity refers to changes in research output that are not explained by changes in the stock of scientific knowledge as proxied by current and past R&D spending. Our estimation of stock of knowledge already controls for the fact that there are some adjustment lags and that a given increase, for example, in the Science Budget, is not going to have an immediate impact on research outputs. In the case of a traditional productivity measure, such as the ratio between papers and HERD, the UK has witnessed a very clear decline in the 1990s due to the significant increase in the Science Budget and not to a deterioration in the performance of the system (Evidence [2003]). Our measure of productivity controls to some extent for this and tries to capture organisational or managerial changes in the system.

Table 8: TFP growth rate decompositions for Natural Sciences and Engineering

| | Natural Sciences | | | | | Engineering | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | A | B | C | D | TOTAL | A | B | C | D | TOTAL |
| 91-96 | 1.5 | 1.4 | 1.4 | 1.2 | 1.1 | 3.0 | 2.8 | 3.1 | 2.8 | 2.7 |
| 96-01 | 0.7 | 0.8 | 0.7 | 0.6 | 0.6 | 1.3 | 1.2 | 1.4 | 1.2 | 1.3 |
| Total | 1.1 | 1.1 | 1.1 | 1.0 | 0.9 | 2.2 | 2.1 | 2.3 | 2.1 | 2.1 |

Note: A controls only for R&D spending; B is A plus controlling for resources allocation by London, 1994 Group and Russell Group; C is A plus controlling for University Age; D is A plus controlling for teaching intensity; and Total is A plus (B+C+D).

The TFP estimations above take account only of the spending on research grant and contracts. We now introduce the other control variables to see whether they explain the productivity slowdown. There are several different, and overlapping, explanations. One is that in the period 1996-2001 the distribution of higher education funding led to the system being less productive within each scientific field (B and C estimations). Another is that increased enrolment rates at undergraduate level were not compensated for by an equivalent increase in staff, leading to a reduction in available research time (D estimation). To investigate these two possibilities we re-estimated the TFP indices controlling for how resources are allocated across types of institutions and for teaching intensity ratio. The results for publications are presented in Tables 8 and 9.

Table 9: TFP growth rate decompositions for Medical and Social Sciences

| | Medical Sciences | | | | | Social Sciences | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Time | A | B | C | D | TOTAL | A | B | C | D | TOTAL |
| 91-96 | 2.0 | 2.0 | 1.9 | 1.3 | 1.2 | 3.2 | 3.2 | 2.7 | 3.2 | 2.8 |
| 96-01 | 1.4 | 1.3 | 1.3 | 1.4 | 1.2 | 1.6 | 1.8 | 1.5 | 1.7 | 1.8 |
| Total | 1.7 | 1.7 | 1.6 | 1.3 | 1.2 | 2.4 | 2.6 | 2.1 | 2.5 | 2.3 |

Note: A controls only for R&D spending; B is A plus controlling for resources allocation by London, Group 94 and Russell Group; C is A plus controlling for University Age; D is A plus controlling for teaching intensity; and Total is A plus (B+C+D).

Two trends emerge from Tables 8 and 9. First, at field level the process of resource allocation has no serious impact on productivity growth because controlling (or not) for how resources are distributed across university types and geographical location (columns B and C compared to column A) only marginally affects average productivity growth. The exception is Social Sciences where the distribution of higher education funding in the first period compared to the distribution in the second period, which led to the system being less productive, reduces the unexplained productivity slowdown (for example, in column A the difference between the two time periods is 1.6; in column C the difference is 1.2).

The results controlling for teaching intensity are similar and, again, are relatively invariant. The exception is Medical Sciences where, after controlling for teaching intensity, productivity growth rate reduce from 1.7% to 1.2% (row total) and the two sub-periods show no productivity slowdown. Interestingly, after controlling for teaching intensity TFP in the first period drops to 1.3, pointing to the fact that the reduction in teaching intensity in this discipline actually contributed to the higher productivity during the first time period.[10] For the other research outputs the conclusions are similar to those for publications.

Controlling for research allocation and teaching intensity partially explains the productivity slowdown in Medical Sciences (especially in the case of publications), but does not account for the productivity slowdown in the second half of the 1990s for the other scientific fields.

There are four possible reasons for this unexplained slowdown. First, there might have been a deterioration in the organisational efficiency of production of traditional science outputs within each field (and even within departments) due, for example, to the creation of incentives for development of third stream type activities. Second, there might have been a reduction in human capital (the quality of labour) i.e. in the research staff. Underlying this hypothesis is the possibility that the lag in the relative compensations paid to researchers in the universities could have led to some 'high

[10] Student to staff ratios in Medical Sciences decreased from 8.4 to 7.4 students per staff across the whole period. A more detailed inspection shows that any decrease was mostly during the first sub-period. The ratio of students to staff in 1991-95 declined annually from 8.4 in 1991 to 6.9 in 1995. This variable was more volatile in the second sub-period oscillating between 6.9 and 7.3.

skilled' staff leaving academia (for positions overseas or for jobs in industry), being replaced by an equivalent number of lower quality personnel. Third, due to the increase in other countries' publishing in English, UK researchers are facing increased competition for publication in ISI journals, raising the bar to getting published (a quality effect).[11]

All of these are pessimistic explanations for the productivity growth slowdown. There is a fourth possibility, which is more optimistic, which is that the RAE has an impact. We can think of the RAE as a sort of institutional shock in the research incentive system for academic units. That is, the introduction of the RAE at the end of the 1980s/beginning of the 1990s produced a positive shock, which induced a productivity increase on the part of UK scientists. If this shock were affecting productivity levels rather than growth rates, after a transition period the system would return to its average growth rate. In other words, the effect of the RAE may have been more dramatic in the early 1990s, but subsequently declined. This could explain the productivity slowdown in the second sub-period considered in our analysis.

It is very difficult to identify which of these potential explanations is the most relevant. Alternative models based on micro data at the university and unit of assessment levels could help to clarify the current dynamics of the UK science system.

## *5 Conclusions*

This paper has analysed the determinants of the three most common university research outputs: publications (as a proxy for the production of codified research knowledge) citations (as an impact adjusted proxy for codified research production); and Masters and PhDs awarded (as a proxy for the production of tacit knowledge accumulated in human capital) for the UK case.

The analysis of the UK science system as represented by the old universities (which account for about 90% of R&D expenditure) points to the existence of different science production functions. We rejected the model of a global science production function for the UK in favour of four very broadly defined macro-fields: Medical Sciences, Social Sciences, Natural Sciences and Engineering Sciences. In each of these fields either the weight patterns or the R&D elasticities (and also some of the coefficients of control variables) were significantly different.

For publications and citations we estimated significantly different lag structures, with a long lag for Medical Sciences before full returns from an increase in R&D spending were achieved, but Social Sciences seeing results in the first few years. This means, that the science system does not respond uniformly to changes in funds. For example, an increase in the overall Science Budget will have a rather sequential impact: first, the changes will be felt mainly in Social Sciences, then in Engineering and Natural Sciences and finally, in Medial Sciences. For graduate student research output the results are different, with the short term impact being concentrated in Engineering and the long term impact in Social Sciences.

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[11] There is some evidence of this phenomenon in the discussion in the *New York Times* [NYT, May 3, 2004] about the loss of dominance of the US in the sciences to non-English speaking countries.

In the case of Medical Sciences, Social Sciences and Natural Sciences we identified positive and significant returns for publications, citations and graduate students from investment in higher education R&D. Although positive the effect in Engineering is only significant in the case of publications, pointing to the fact that the research output of this scientific field is better captured by other measures than citations and research students.

We included in the models a set of control variables. We found strong evidence that a large undergraduate teaching load negatively affects the research outputs in UK universities. Only in the case of graduate students in Social Sciences did we see a positive effect. Overall, the higher the teaching load the lower the research productivity. This result denies the validity of the policy model followed in the 1980s and 1990s, which assumed that the number of students per lecturer could be increased without a decrease in the overall quality of the HE system.

We also controlled for the impact of different allocations of funding across types of institutions; the results are mixed and vary according to the different research outputs. Some were significant pointing to the fact that different allocations of funds to universities result in higher or lower university system scientific production Due to the limitations of field level data, the results on university specific factors, though interesting, should be considered as preliminary: they require validation through analyses based on micro data.

Finally, we developed an analysis of the productivity of UK science and the changes in it during the 1990s. UK TFP has grown across the whole period. This result contrasts with the most standard Publication per HERD measure of productivity, which presents a remarkable drop in British productivity, mainly due to a combination of increased budget and publication lags. However, we also identified a clear slowdown in TFP growth in the second half of the 1990s compared to the first. This decline is not due to an increase in the research spending in the later period, nor to the way that resources were allocated across institutions (although this did have some effect in Medical Sciences and Social Sciences), nor to an increase in teaching loads (which were fairly static in the second half of the 1990s). We speculate that this slowdown in productivity is due to mainly unobserved systemic effects (a policy shock during the first half of the 1990s such as the RAE) or very micro factors related to the (relative) reduction in researchers' rewards, the introduction of more transferable research or a 'brain drain' of high skilled researchers. This slowdown can also be ascribed to increased competition for publication in ISI journals from overseas research. Without more micro data it is not possible to tease out from these alternative explanations their relative importance. These results are consistent with the results of international analysis, which point to a decrease in the relative productivity of UK science. Indeed, it is possible to envisage that, during the 1990s, UK science showed positive productivity growth, but that this growth was less marked than in other countries, especially in the second half of the 1990s.

This paper aimed to test the feasibility of using econometric models to produce results that could contribute to the development of science policy, the aim being not to produce exact indicators of the dynamics of the science system, on the basis of which to draw strong policy conclusions. Rather, the inherent shortcomings in the measurement of the output (and ultimately of the outcomes) of the scientific activity, and the limitations on the available input data call for extreme caution in the interpretations of our results. The conclusions presented above should be taken as a first and preliminary attempt to develop a better understanding of the relationship between the allocation of resources and scientific research output.

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Figure 3.1 Restricted Pattern of Weights (Publications), by fields

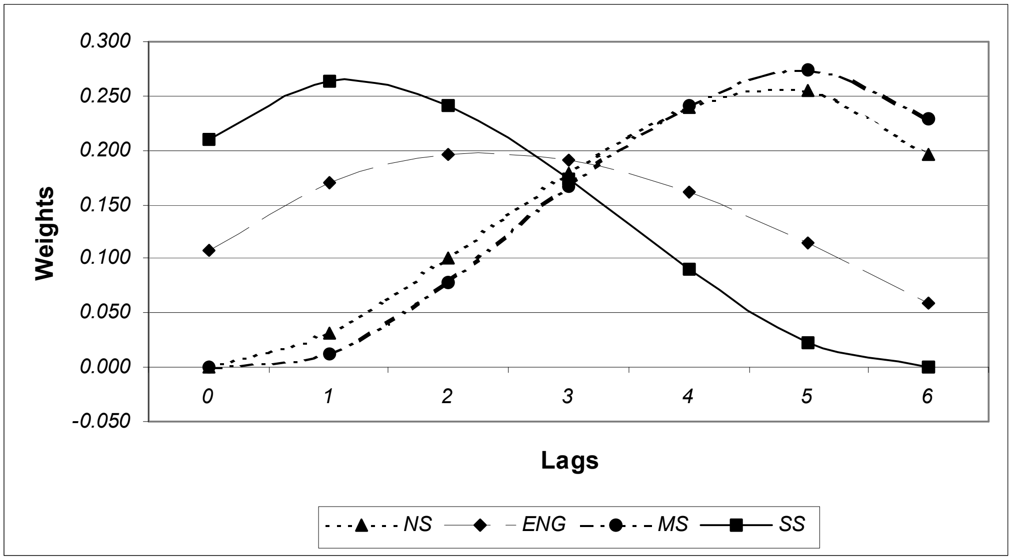


Figure 3.2 Restricted Pattern of Weights (Citations), by fields

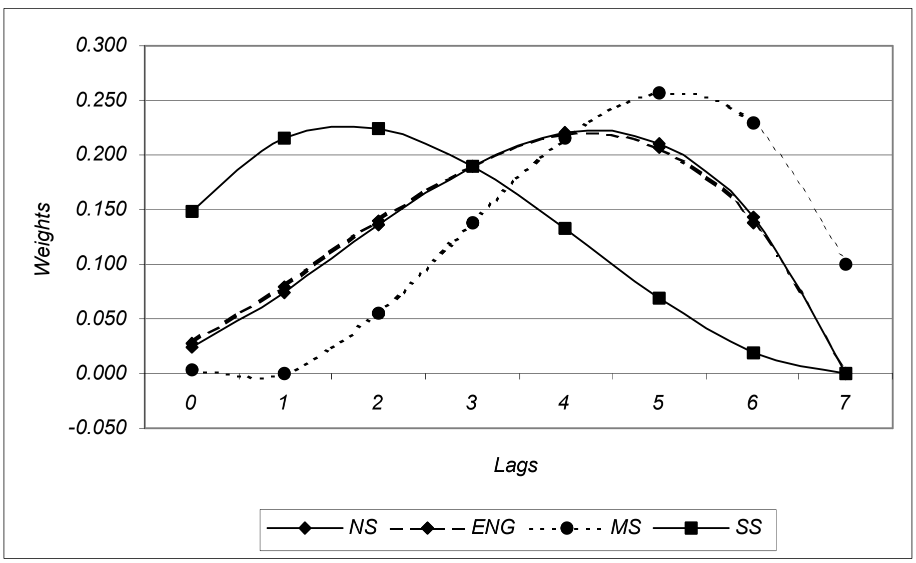

Figure 3.3 Restricted Pattern of Weights (Graduate Students), by fields

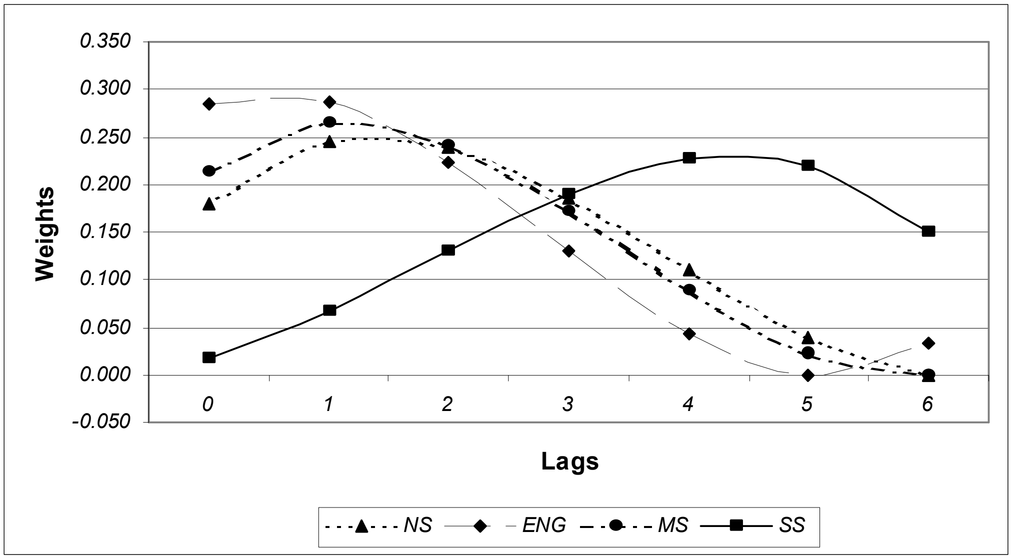


Figure 4.1. TFP Publications

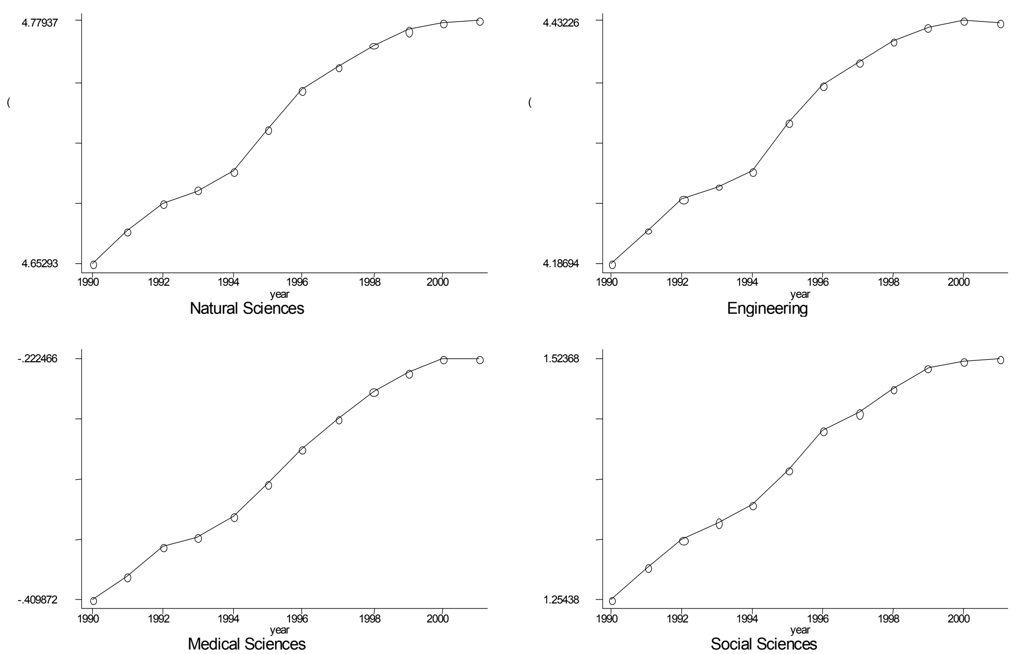

Figure 4.2. TFP Citations

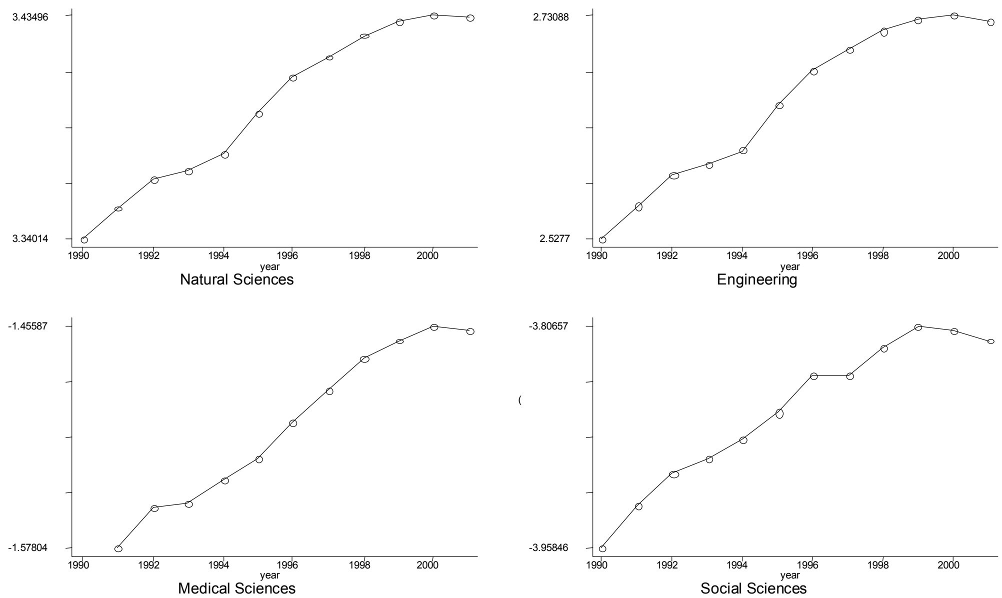


Figure 4.3. TFP Graduate Students