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The Productivity of Science

Gustavo Crespi & Aldo Geuna

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SPRU- University of Sussex

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Contact

Aldo Geuna
SPRU, University of Sussex,
Freeman Centre,
Brighton BN1 9QE, UK;
Tel. +44 1273 877139;
Fax. +44 1273 685 865,
e-mail a.geuna@sussex.ac.uk

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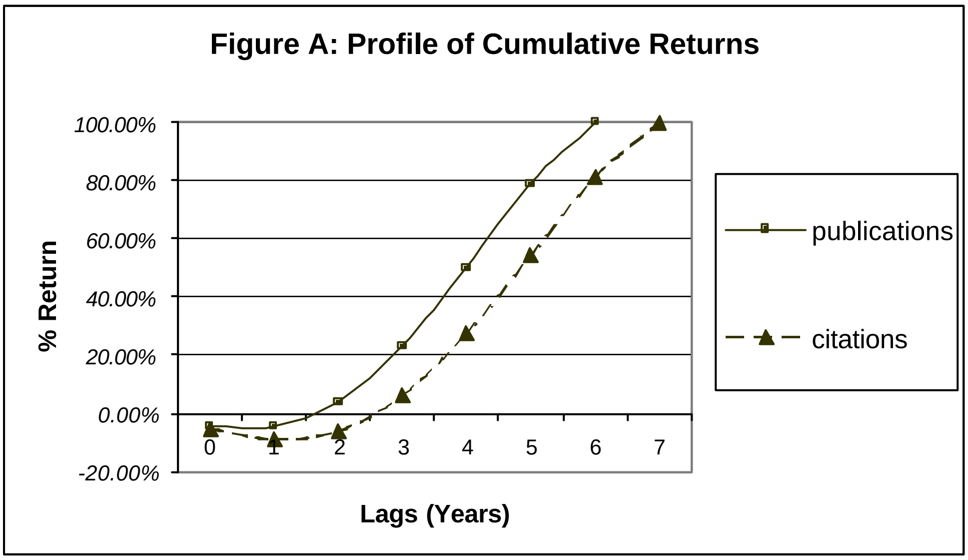
Executive Summary

i. A great deal is known about the productivity of investment in research and development in firms compared to our current understanding of the determinants of the scientific research output of higher education institutions. Given the increased interest of policy makers and society at large in the role and productivity of universities, more research is needed on the productivity of science at both the national and international levels. This report represents a first attempt in this direction; we studied the international productivity of science in terms of the returns from investment (elasticity), length of time before returns are reaped (lag structure) and the countries that are catching up or falling behind in term of scientific productivity (dynamics of productivity).

ii. Due to the time needed to conduct a research project and get an article published, the effects of any increase in the science budget on publication output and citations earned are likely to be distributed over time. Analyses of scientific productivity or performance that do not include a time lag between investment and outputs will almost certainly be misleading. It takes six years for publications and seven years for citations before the full effect of an increase in Higher Education research and development spending is achieved. For the first two years there is no significant return from investment. In the case of publications, by the end of four years about 50% will have appeared, while for citations it is five years before this 50% threshold is reached (see Figure A: Profile of Cumulative Returns).



iii. For publications and citations we found evidence of decreasing returns to the domestic component of Higher Education research and development (the more is invested, the less is the per £ return). Long-term elasticities (which measure the total effect of an increase of £1 after the lag period) for the national investment in science are of the order of 0.4 for publications and 0.5 for citations. That is, a 1% change in domestic Higher Education research and development spending leads to about a 0.4% change in publication output and 0.5% in citations.

iv. We identified significant international spillover effects for both publications and citations (with a long-term elasticity of about 0.5). A country's scientific output is affected not only by the national investment in science, but also by similar investment in other countries. This phenomenon is mediated by the knowledge proximity (in terms of knowledge exchange or cooperation) of different countries as measured by the relative level of co-authorship in the period considered.

v. The international science system (represented by the 14 leading countries analysed here) shows decreasing returns to scale at the national level, but slightly increasing returns at the international level. When spillovers are included in the estimation, the sum of domestic elasticity plus spillover elasticity is slightly above 1. Bearing in mind that the scientific system is characterised by open and free exchange at the international level, an increase by all the considered countries will result overall in a slightly higher than proportional return at the international level. The greater the investment in science the bigger the incremental benefit from it.

vi. Cross-country comparability problems are inherent in the data on Higher Education expenditures on research and development; thus, productivity league tables are not necessarily a robust indication of the relative ranking of countries in terms of scientific productivity.

vii. If we think of relative scientific productivity as the distance from the efficient technological frontier (the distance of the science system from the current best way of producing science output) we can explain productivity in terms of different organisational structures (different organisations in national science systems are linked to different distances from the optimal output). On this basis, we analysed catching up and falling behind in relative scientific productivity. Several interesting results emerged. First, the US and the UK science systems are the most technologically efficient (the best organisational set up and the highest productivity). Second, most of the countries considered, except the US, Australia, Canada and the UK, have positive productivity growth rates relative to the most efficient technological frontier (although Switzerland and The Netherlands might appear to have negative productivity growth, this is only weakly statistically significant in the case of citations). All countries are converging towards the 'efficient frontier' represented by the US. Third, the convergence of the UK with the US is mainly due to a deterioration in US productivity. The productivity growth rate of the UK relative to the most efficient technological frontier has declined across the period, but more slowly than in the case of the US. Fourth, the remaining countries are catching up with the UK either because (with the exception of Canada) they show positive or zero change in productivity, or because their rate of decrease is not as great as that for the UK. There are a number of possible explanations for this, including changing publication behaviour of the lower ranked nations, science policy reforms in these countries to encompass international good practices, and greater emphasis on commercialisation in the leading nations. In future work we intend to explore this issue further.

viii. Preliminary analysis of the impact of the science budget on the 'production' of PhD students suggests that the increase in investment in Higher Education research is connected with a significant rise in the number of graduates in a country. The results indicate a long-run elasticity close to 1, leading to the conclusion that there are constant (or slightly increasing) domestic returns to scale.

ix. Due to differences in the way in which the sources of Higher Education expenditures on research and development are recorded across countries and along time, accurate estimation of any 'crowding out' or 'crowding in' phenomenon is likely to require more robust country level data. The important conclusion that emerges from the analysis presented here is that an increase in the government budget for Higher Education research and development could induce either further investment from other sources (i.e. 'crowding in' of business funds in our example) or a reduction in funding (i.e. crowding out of other sources of funds in our example). These direct effects have to be assessed along with the complementary indirect effects influencing the various sources of funding. In the estimates presented here, the overall effect was not significant, meaning that there was no evidence of either crowding in or crowding out.

x. We analysed the science production of the 52 'old' UK universities that accounted for about 90% of Research Grant and Contract income in 2001. Scientific production varies according to the scientific field considered. A national level science production function model was statistically rejected in favour of four very broadly defined macro-fields: Medical Sciences, Social Sciences, Natural Sciences and Engineering Sciences. We found that for each field either the weight patterns or the R&D elasticities were significantly different. Also, the significance and value of a set of control variables explaining the science output vary across scientific fields.

xi. Returns from investment in higher education R&D were positive and significant in the case of Medical Sciences, Social Sciences and Natural Sciences for publications, citations and graduate students, whereas in Engineering the only positive effect was in publications. This evidence seems to indicate that the research output from Engineering Sciences should be captured by other measures than citations and research students.

xii. Significantly different lag structures were identified for publications and citations showing that the science system does not respond uniformly to changes in the sources of funds. Medical Sciences showed a long lag before full returns from R&D spending were achieved while the results in Social Sciences can be seen within the first few years. The impact of an increased Science Budget is sequential starting with Social Sciences then being apparent in Engineering and Natural Sciences and finally appearing in Medical Sciences. Interestingly, when we considered the graduate student research output, Social Sciences is the only scientific field that requires a long period before full returns are achieved. It takes more than 5 year to obtain 90% of the impact for Social Sciences, while for the other three fields roughly 90% of the returns are achieved within 3 years.

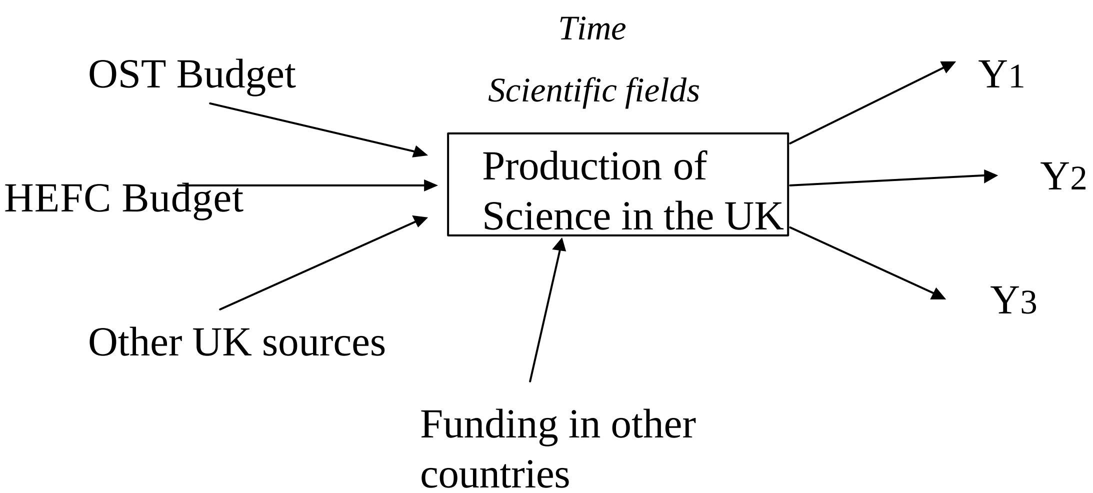
xiii. Although limited in our analysis by the fact that we could only access output data at the field level, we succeeded in highlighting a set of interesting university specific phenomena. The impact of different allocations of funding across different types of institutions was mixed, and varied according to research outputs. However, the results showed that different allocations of funds to universities do affect scientific production. The higher or lower output can be due to higher productivity in the institutions that received bigger grants and more contracts or to a competition effect from the universities that received less funding. We also found strong evidence that undergraduate teaching loads had a negative effect on universities' research output in Medical Science, Natural Sciences and Engineering. On the other hand, in Social Sciences we found a positive impact from undergraduate teaching towards graduate teaching, pointing to an apparently different nature of graduate studies in this field.

xiv. We have developed an analysis of the changes in UK science productivity. Overall our analysis shows that across the whole of the period examined total factor productivity increased. This result contrasts with the Publication per HERD measure of productivity that usually points to a decrease in productivity of UK science. However, if we look at the second half of the 1990s our analysis shows that there was a clear slowdown in productivity in this period. These results are consistent with the results of the international analysis pointing to a decrease in the relative productivity of UK Science. Although during the 1990s UK science shows positive productivity, this growth is less marked than in other countries. Various explanations for this decline have been put forward, but due to data constraints we were only able to develop a preliminary test for two of them: the way that resources were allocated across institutions and the increase in teaching loads (which were fairly static in the second half of the 1990s). Neither was a major reason for the slow down. We speculate that this slowdown in productivity could be due to other reasons. First, there might have been a deterioration in the organisational efficiency of production of traditional science outputs within each field 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 due to some of 'high skilled' staff in UK academia taking up positions overseas or in industry and being replaced by an equivalent number of lower quality personnel. Third, due to the increased publishing in English by other countries, UK researchers are facing stronger competition to get their papers published in ISI journals, raising the bar to getting published (a quality effect). Fourth, the UK science system experienced a temporary increase in productivity during the first half of the 1990s resulting from the 'policy shock' of the introduction of the RAE.

1 Introduction

There is increasing recognition among the OECD countries of the importance of scientific research in providing the foundations for both innovation and competitiveness. This has resulted in increasing amounts of public funding for such 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 examining the effects of public funding of basic research on the innovative activities of firms, bypassing the whole question of how to measure scientific output. The main reasons for this lie in the difficulty of identifying a stable causal relationship between the resources spent on the science budget and 'intermediate' scientific outputs. These difficulties originate from the dynamic nature of the problem. There is a persistent and therefore recursive feedback between inputs and outputs, and this is exacerbated by the lack of appropriate information for analysis.

Figure 1.1



As can be seen from Figure 1.1, there are several sources of funds that feed into the national science budget. For example, the Higher Education sector performed a total of £ 4,035 millions in research and development in 2001; this amount was financed by: 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)[1]. All these funds are then allocated within the system according to scientific field and research institution, thus providing the inputs needed for carrying out research. The scientific process produces several research outputs that can be classified into three broadly defined categories, represented in the diagram by 'Y': (1) new knowledge; (2) highly qualified human resources; and (3) new technologies. This report focuses on the determinants of the first two types of research output, which are those most closely related to the science research budget. There are no direct measures of these two research outputs, but several proxies have been used

[1] The source of this information is Office of National Statistics, R&D performed in the UK in each sector according to source of finance: 1979-2001.

in previous studies. The three most important ones that we will apply during this study are (a) publications, (b) citations and (c) numbers of PhD degrees awarded. The source of the first two variables is the Thomson ISI(R) 'National Science Indicators' (2002) database on published papers and citations. The source for the data on PhDs awarded is the OECD 'Education at a Glance' database.

In this report we focus on the determinants of research output at the international level. We use a sample of 14 countries (all of them members of the OECD) for which we have information about Higher Education Research and Development (HERD) (HERD) and its components. The inputs and outputs for this sample of countries have been recorded over a period of 21 years (1981-2002). On the basis of this panel dataset we aim to provide preliminary answers to the following research questions:

i. What is the profile of the time lag between investment in HERD and research output? Does it vary according to output being considered?
ii. What are the returns to national investment in science? Are there cross-country spillovers?
iii. In which countries is scientific productivity similar? What is the position of the UK in the productivity 'League Table'?
iv. Are these countries catching up with the leaders or falling behind them in scientific productivity? What is the relative position of the UK?
v. Does an increase (or decrease) in government investment in public science crowd out other sources of funds or does it have the opposite effect (i.e. crowding in)? Have business sources of R&D funds substituted for government funding in the last 20 years?

The data on higher education research and development (R&D) expenditure suffer from major cross-country comparability problems, such as different definitions of which institutions are included in the category 'HE' (for example, CNRS laboratories are included in HERD in France while similar institutions in Italy, i.e. CNR laboratories, are included in the 'government' R&D expenditure category), and different ways of classifying HE expenditures in the various countries (e.g. PhD students in Sweden and The Netherlands receive a salary, but those in the UK and Italy only receive a grant) (Geuna, 2001; Jacobsson and Rickne, 2003). These differences limit the validity of cross-country comparisons. In particular, although five different econometric techniques have been deployed in this study, the comparative efficiency analysis is based on the number of publications and citations by country has resulted in non-robust econometric results (in relation to question iii above). The following sections present the results of a set of econometric models developed to provide some empirical evidence to answer the research questions i, ii, iv and v above. Section 2 focuses on the first two research questions, while Section 3 is devoted to a preliminary attempt to develop a robust econometric estimation of technological efficiency to provide information on scientific productivity and its variation across countries. Section 4 is devoted to a first examination of the relationship between science spending and numbers of PhD students. A model to study crowding in and crowding out phenomena in the case of multiple sources of funds is presented in Section 5. Section 6 focuses on field specific science production functions for the UK. Finally, in the conclusions we put forward a possible use of the results in a simple predictive model.

2 Models to Examine the Relationships between Science Funding and Research Outputs: An international analysis

2.1 Preliminary Analysis of the Data

In order to predict the system-wide impact of the science budget on the different research outputs we examine publicly available information on Higher Education R&D expenditure and its components at country level. The OECD defines the Higher Education sector as all universities, colleges of technology and other institutions of post-secondary education, whatever their source of finance or legal status. This includes all research institutes, experimental stations and clinics operating under direct control of, or administrated by or associated with the higher education institution (OECD 2002). Because this sector does not usually directly match with the System of National Accounts, it is difficult to provide clear guidelines that ensure internationally comparable data reporting. Universities and colleges of technology make up the core of the sector in all countries. Variations occur with respect to other post-secondary education institutions and even more so to several types of institutes linked to universities, such as university hospitals and clinics. A case-by-case analysis was carried out in order first to identify 'major' structural breaks in the series and second to identify a set of comparable countries with comparable statistics.[2] However, because 'permanent' country level differences in the way that information is collected might remain, we need to control for these systematic differences in the estimations.[3]

On this basis we focused our analysis on the following 14 countries: Australia, Belgium, Canada, Finland, Denmark, France, Germany, Netherlands, Spain, Italy, Switzerland, Sweden, UK USA. We could not include countries where the information about HERD statistics was missing from the original Evidence dataset i.e. Brazil, China, India, Iran, Israel, Russia, Singapore, South Africa and Taiwan. Neither could we include those countries in the OECD dataset where, although the information about HERD was available, it was very incomplete and/or inconsistent (this includes Austria, Czech Republic, Greece, Hungary, Iceland, Ireland, Mexico New Zealand, Poland, Portugal, Slovak Republic, Turkey, Norway and Japan). The HERD figures that we used are expressed in millions of constant US$ as reported by the OECD. R&D expenditure series were deflated using the implicit GDP deflator taken from the OECD National Accounts database. These national currency data at 1995 prices were converted to US$ using 1995 purchasing power parities (PPP).[4]

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[2] In particular all the models presented in this report were first estimated on a country-by-country basis and then different dummy variables were included if there was some report about changes in the classification criteria. Only those countries for which results were robust to these breaks were considered.

[3] More specifically, a country level fixed effect was always introduced into the different models. This fixed effect not only captures permanent differences relating to the functioning of the various national scientific systems, but also differences in how the information is collected. More particularly, for almost all the results shown below we worked with 'within' country information and 'averaged' to achieve a global estimation. We can deploy this approach due to the panel data nature of the dataset we have built.

[4] The fact that we are using the GDP deflator instead of the correct HERD deflator induces a sort of omitted variable bias. If the HERD deflator shows a long run increasing trend compared to the GDP

Additionally, the dataset used here has information of the aggregate research outputs by country. Hence, we are not controlling, in this step, for differences across scientific fields. Given the fact that publication and citation propensities vary across disciplines, if the research portfolio of each country has a different mix of scientific fields the estimations may be affected. However, if each country's research portfolio were stable over time, these sorts of differences would be also absorbed by a country level fixed effect. Unfortunately, the lack of sufficiently detailed information precluded us from testing this assumption.[5]

In order to take into account the 'truncation problem' in the citations for most recent years, the citations variable has been adjusted.[6] One way of controlling for this is by using what Hall et. al (2001) called the fixed effect approach. This method involves scaling citations counts by dividing them by the average citation count for a group of publications to which the publication of interest belongs. Using the same example as in Hall et al., this approach treats a publication that received say 11 citations and belongs to a group in which the average publication received 10 citations, as equivalent to a publication that received 22 citations, but happens to belong to a group in which the average was 20. The groups were defined in terms of scientific fields and year and the scaling index was computed using the ISI dataset at world level.

For the 14 countries examined we present country level graphs of research output and lagged values of the corresponding financial input (HERD). Figure 2.1 shows the relationships between (log) publications and (log) HERD with two-year lags; Figure 2.2 captures the same relationship between (log) citations and (log) HERD with four-year lags. Here we follow Adams and Griliches (1996) who found that these are the 'minimum' time lags before we should expect to 'see' the results from a given research. In any input-output analysis in which the input is R&D it is crucial to include at the least a minimum time lag between input and output. This is especially so in the case of science where the time needed first to transform an original idea into codified knowledge suitable for publication, then to proceed to the publication process and eventually arrive at the published paper is relatively lengthy.

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deflator, the time trend variable included in the econometric models will capture this. See Appendix A for details.

[5] For the analysis of the differences in the science production function across broadly defined scientific fields in the UK case, see section 6.

[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 just from papers published in the period 2000-2001, but in fact they will be cited by papers in subsequent years as well, but we do not observed them.

Figure 2.1 R&D and Papers by Country

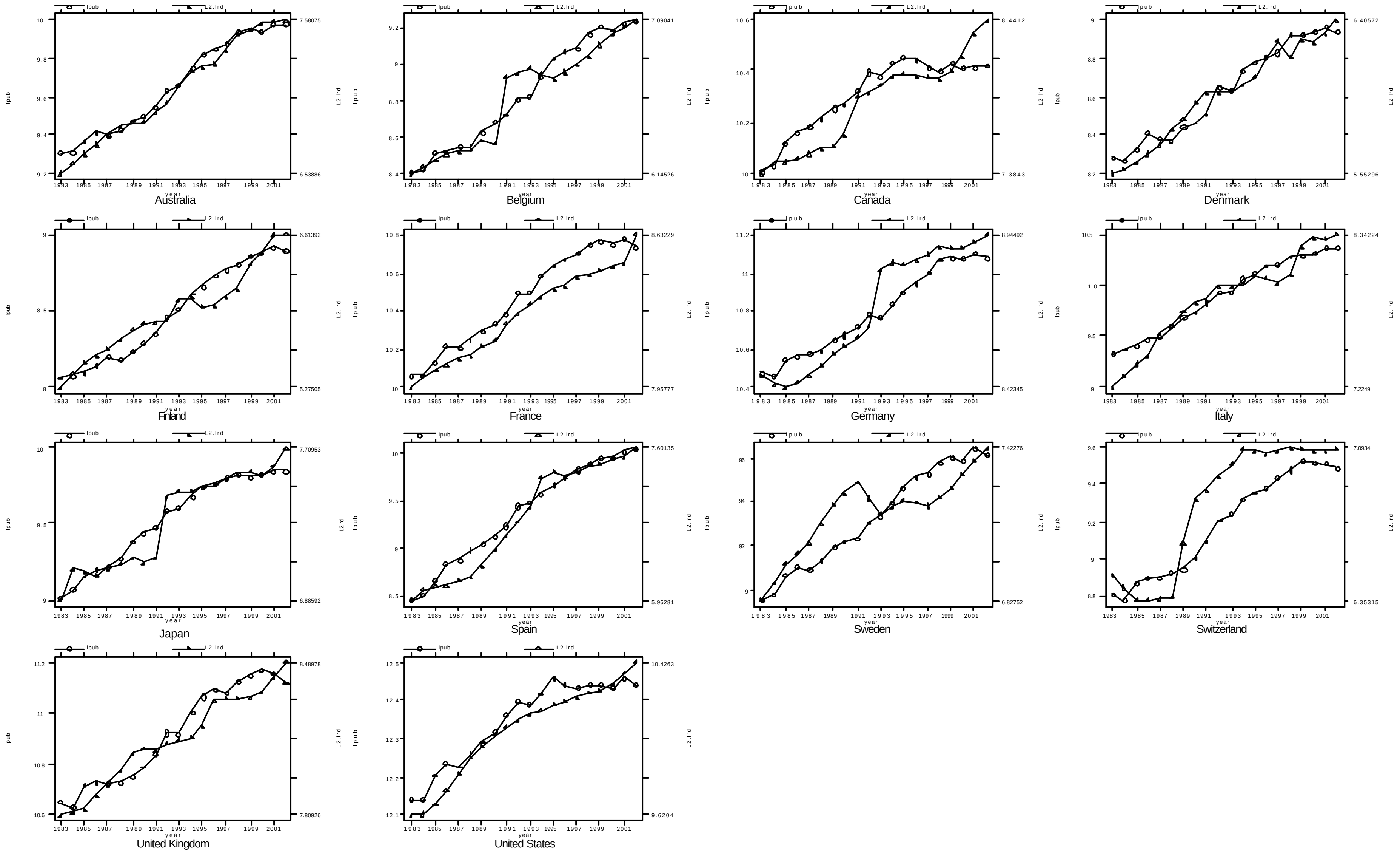
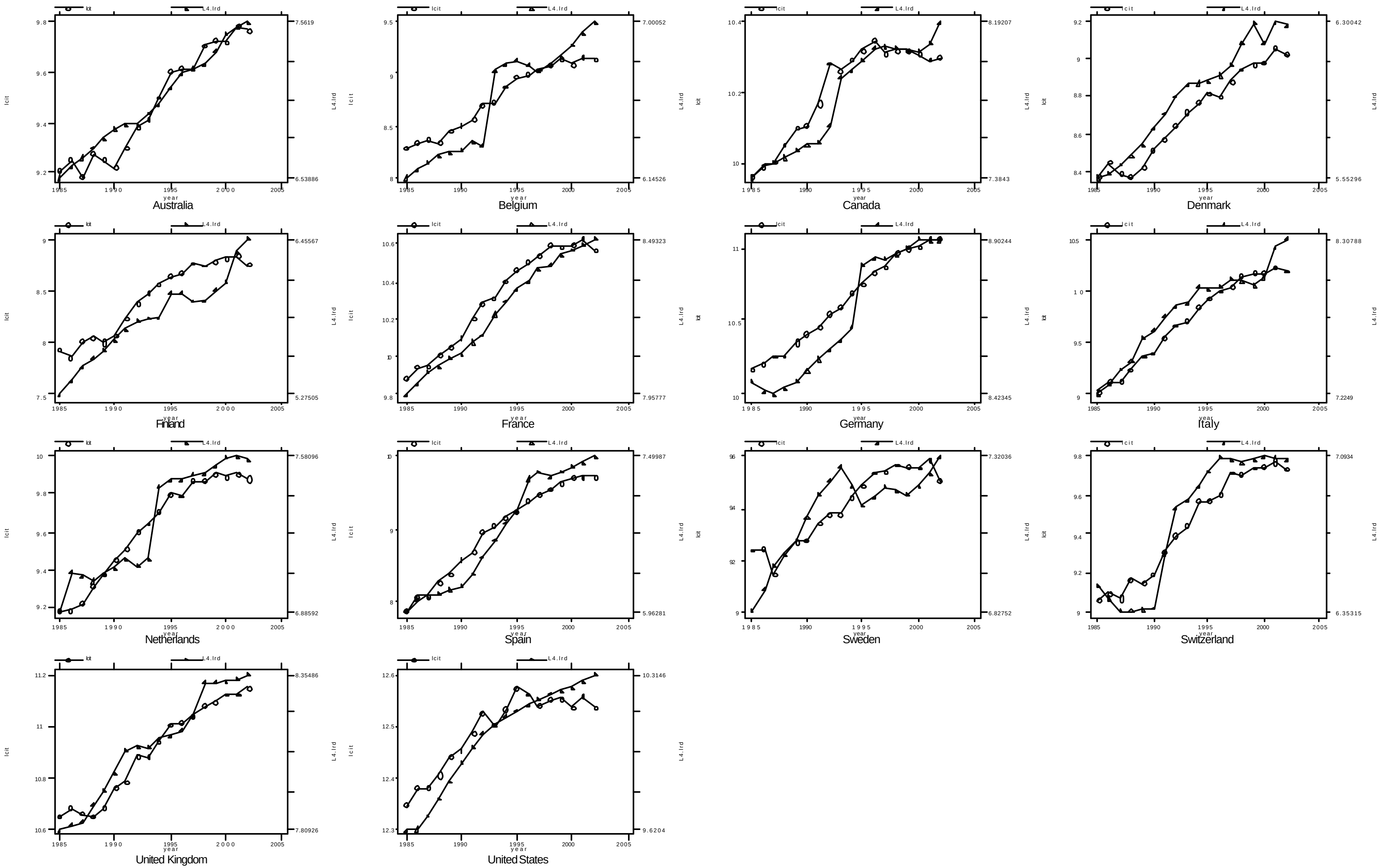


Figure 2.2 R&D and Citations by Country



Both figures depict time on the horizontal axis and measure the level of input (HERD) and outputs (publications and citations) on the vertical axis. Since inputs and outputs are measured on log scales, the slopes of the curves represent growth rates, permitting comparisons between research outputs and inputs. With very few exceptions, the country level graphs in both figures show similarities in the growth rates of lagged R&D (input) and papers and citations (outputs).

Another important conclusion that can be drawn from these figures is the fact that both publications (and citations) and HERD expenditure are very persistent series over time. This very much complicates the statistical inference because these series can be correlated due to the presence of a third common variable (the time trend) leading to spurious or overestimated results.

In order to see what kind of stochastic process governs the series, we carried out several tests. Unit root tests are used to determine whether it is better to work with first differenced observations (because they have a unit root) or to control by a time trend in the models (because they are trend stationary series). The results are explained in the Appendix B. However, it is important to say here that we can consider the series as stationary, but with a deterministic trend. In what follows we work with these series in levels and we add a deterministic trend to the models.

In the following four sub-sections we briefly present the estimation of the relationship between HERD and scientific output according to two traditional models already developed in the literature (Sections 2.2 and 2.3). We use these as benchmarks for the econometric model developed in Section 2.4. Once we have identified the lag structure we focus on the search for international spillovers. Section 2.5 presents the final estimation of our model (see Table 2.10), which includes both national and international HERD expenditures.

2.2 The Griliches–Adams Benchmark

Our first exercise is to use the standard knowledge production function model outlined in Adams and Griliches (1996) as a benchmark for our results. They use the following expression:

$$y_{it} = a_i + b W(r)_{it} + g_i X_{it} + u_{it}, \quad i = 1, \ldots . N \quad (1)$$

where y_{it} is the (log) output of the research 'intermediate' output (papers and citations) by country i (we have 14 countries) and time t (21 years). $W(r)_{it}$ is (the log of) a distributed lagged function of real past R&D expenditure and X_{it} is a vector of the control variables.

In our estimation we used two control variables: a time trend that captures the evolution of the general scientific opportunity and the proportion of non-HERD R&D in the total country research budget. This last variable deserves a bit more attention. The rationale for including it derives from the fact that our 'observed' research output is the total (not only HE) country-level publications and citations. Even when more than 80% of the publications generated by a country are typically the consequence of the research being carried out in higher education institutions, there is still a small proportion produced by firms and other non-university research centres. We expect that non-HERD institutions have a lower productivity in terms of publications and citations than universities. Publications and citations are a by-product of their innovation activities or research supporting government actions. An increased proportion of non-HERD R&D in total GERD would lead to a reduction in total publications and citations. In order to control for this, we built a new variable defined as the ratio between non-HERD R&D and GERD.

The main focus of this analysis is on β, 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 $\beta<(\geq 1)$. Following Adams and Griliches (1996), we present the results of three and five year distributed lags of R&D. The three-year lag uses inverted U weights of 0.25, 0.50 and 0.25 on HERD expenditures in periods t-3, t-2 and t-1, while the five-year lag uses weights of 0.111, 0.222, 0.333, 0.222 and 0.111 on HERD expenditures for periods t-5, t-4, t-3, t-2 and t-1. An inverted U-shaped lag structure is due to the fact that a research project is usually a lengthy and time-consuming activity that can take more than two years to complete and thus to produce measurable outputs. After a few years, due to spillovers and scientific obsolescence of the created knowledge, the returns from the investment become zero (for details of this issue, which also applies to company based knowledge creation, see Griliches, 1998).

Finally, in order to take into consideration the presence of 'un-observed' country level heterogeneity, such as that generated by the presence of local specificities in each national innovation system, we have included a country-level fixed-effects term.

In Table 2.3 we present the results of estimations of this model. We will use them as a benchmark for the following models. The HERD elasticities appear very stable across different lag structures with a value of about 0.48 for publications and about 0.70 for citations.

Table 2.3: Results using Griliches and Adams (1996) Approach (Fixed Effects)

	Publications (3 Lags)	Publications (5 Lags)	Citations (3 Lags)	Citations (5 Lags)
HERD	0.479	0.494	0.695	0.715
	0.051***	0.051***	0.071***	0.069***
Non-HERD	-0.003	-0.003	-0.009	-0.009
	0.003	0.002	0.003***	0.002***
Year	0.020	0.019	0.015	0.014
	0.002***	0.002***	0.003***	0.003***
Constant	-34.108	-31.191	-24.970	-21.906
	4.499***	4.600***	6.337***	6.241***
Observations	266	238	266	238
R-squared	0.89	0.89	0.86	0.87

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

These results suggest the presence of diminishing returns to scale at the country level because the estimated elasticities are well below unity. As Adams and Griliches (1996) found for American universities, the elasticity for citations is always higher than for publications. Regarding the other results, the deterministic time trend is highly significant and positive. Its value suggests a growth rate of about 1.5% to 2% in the output connected to time. After controlling for changes in HERD expenditure, the structure of R&D allocations in each country and other country fixed-effects, we identified a positive growth trend in scientific output. Possible reasons for this could lie in the increased propensity to publish more papers based on the same research or in the fact that the recombination of knowledge can give rise to more output. Finally, as expected, the proportion of non-HERD spending is negatively related to the production of publications and citations (but is only statistically significant in the latter case).

There is a series of problems with this specification. The most important is the way in which HERD is weighted in order to build the stock of knowledge. The number of lags (3 or 5) is determined in a completely ad hoc way, and a U-shaped structure of the lag is assumed, although with reasonable justification. In what follows, we present two alternative ways to deal with these limitations. First, we use the framework of the dynamic panel data literature; secondly, we develop a procedure to estimate a flexible lag structure and the optimum number of lags.

2.3 The Production Function with Adjustment Costs Model

The estimation of a production function with some sort of costs-of-adjustment mechanism in the stocks has increasingly become the benchmark for productivity studies - in particular at the firm level (Griliches, 1998). This approach can be straightforwardly extended to our context as follows.

Let us assume the following knowledge production:

$$Y_{it}^{*} = A_i e^{\lambda t} C_{it}^{\beta} \quad i = 1,2....N; t = 1,2,.....T \quad (2)$$

where Y^* represents the *'optimum or long-run research output'* of country i at time t, λ is the growth rate of scientific opportunity and C_{it} is the '*domestic stock of knowledge*'; while β and λ are the parameters of interest. This same model can be written in a linear form as:

$$y_{it}^{*} = \alpha_i + \beta c_{it} + \lambda t \quad (3)$$

where the small letters represent the logs of the original variables. We can interpret equation (3) as capturing the long-run relationship between the research output and the different sources of knowledge available for each unit in the panel. In this context, the constant absorbs all the idiosyncrasies of the national system of innovation.

One significant problem with equation (3) is that neither of the variables is observed in the real world. Although we can find some proxies for the dependent variables using publications, citations, etc., they are proxies for the 'observed' research output but not for the optimum, and we still lack information about the main explanatory variable (the stock of knowledge). In addition to this, there are potentially important costs of adjustment that make equation (3) meaningless in the short run (e.g. if we increase the stock of knowledge at time t, this is going to produce an increase in the research output but only over time: it takes several years to carry out the research, to write a paper and to get it published). This means we can specify a cost of adjustment mechanism where only a proportion of the gap between the 'observed' research output and the 'optimum' research output is closed every year. That is:

$$y_{it} - y_{it-1} = (1-r)\left(y^{*}_{it} - y_{it-1}\right) + n_{it} \quad 0 < r < 1 \tag{4}$$

where y_{it} is the observed research output. It is useful to re-write equation (4) as:

$$y_{it} = (1-r)y^{*}_{it} + r y_{it-1} + n_{it} \tag{5}$$

The final empirical form of the model is obtained by substituting (3) into (5) in order to obtain:

$$y_{it} = (1-r)(a_{i} + b c_{it} + l t) + r y_{it-1} + n_{it} \tag{6}$$

The equation of interest can be re-defined as:

$$y_{it} = a'_{i} + b' c_{it} + l' t + r y_{it-1} + n_{it} \tag{7}$$

where the term (1-ρ) has been absorbed by the other parameters of the model. The model in equation (7) is a member of the '*dynamic panel data*' models family and this has the advantage of producing both long-run and short-run elasticities. Indeed, the short-run elasticity of research output to the domestic knowledge is β, while the long-run elasticity is given by:

$$b = \frac{b'}{(1-r)} \tag{8}$$

which is well defined under the standard assumption of ρ being in the interval (0,1). The same definitions are also valid for other control variables added to the model. The transition elasticities are given by the geometric sequence:

$$b^{j} = b'(1 + r + r^{2} + \dots + r^{j}) \tag{9}$$

The expression in parenthesis declines exponentially towards zero over time. In terms of the estimation, there are two empirical problems with the model in equation (9). First, the model cannot be estimated by ordinary least square (OLS) because there is '*by definition*' a correlation between the lagged dependent variable and the typical OLS error ($\alpha_i + v_{it}$) generated in the 'omitted' heterogeneity. The second problem is the fact that the domestic stock of knowledge is a not an observed variable.

One way of approaching the first problem is to eliminate the unobserved heterogeneity among different innovation systems. There are two methods for doing this: (a) formulating the model in terms of growth rates (by taking the first difference) or (b) applying the within transformation as we did in the benchmark in the previous section. Following the first approach the model can be written as follows:

$$\hat{y}_{it} = l' + b'\hat{c}_{it} + r\hat{y}_{it-1} + n_{it} - n_{it-1} \quad (10)$$

where the ‘^‘ means that the variables are growth rates. The dependent variable is the research output growth rate (i.e. the publications growth rate) but what are the independent variables? Following Griliches (1980), for those stock variables whose initial level is rather low while the rate of growth of the investments of those stocks is rather high, we can use the assumption of proportionality and proxy the knowledge growth rates by the research and development growth rates. The rationale is as follows: assume no depreciation and let the research expenditures R grow at the constant rate ϕ; then the rate of growth of the domestic knowledge stock, say g, is given by:

$$g_t = \frac{R_t}{C_{t-1}} = \frac{R_0(1+f)^t}{\sum R_{t-1-i}}$$

$$= \frac{R_0(1+f)^t}{R_0 \sum (1+f)^{t-1-i}}$$

$$= \frac{(1+f)}{\sum \left[\frac{1}{(1+f)}\right]^i}$$

$$= \frac{(1+f)}{\frac{1}{\left[1 - \frac{1}{(1+f)}\right]}} = f$$

Hence an empirically estimable form of this model becomes:

$$\hat{y}_{it} = l' + b'\hat{r}_{it} + r\hat{y}_{it-1} + n_{it} - n_{it-1} \quad (11)$$

One problem with model (11) is that the error has autocorrelation and this, together with the lag of the dependent variable at the right hand side, leads to a ‘negative’ correlation between this variable and the error. In synthesis, while OLS introduces a positive correlation between the lagged dependent variable and the error (which leads to an upwards bias in ρ), the growth rate specification generates a negative correlation (which leads to the downward bias in ρ). The true parameter will lie somewhere in between.

The second approach gets rid off the unobserved heterogeneity by applying the within transformation. This approach eliminates the source of bias by transforming the equation to eliminate (α_i). Specifically the mean values of the variables across the T-1 observations of each individual are obtained and the original observations are expressed as deviations from these individual means. OLS is then used to estimate these transformed equations. Since the mean of the time invariant (α_i) is itself (α_i), these individual effects are removed from the transformed equations. That is, we estimate:

$$y_{it}^{W} = l' t^{w} + b' r_{it}^{W} + r\hat{y}_{it-1}^{W} + n_{it}^{W} \quad (12)$$

where again we are approaching the within capital stocks by using the within research and development expenditures. However, following Bond (2002) this transformation also induces a non-negligible correlation between the transformed lagged dependent variable and the transformed error term. The transformed lagged dependent variable is:

$$y_{it-1} - \frac{1}{T-1}\left(y_{i1} + \ldots + y_{it} + \ldots. + y_{iT-1}\right)$$

while the transformed error term is:

$$n_{it} - \frac{1}{T-1}\left(n_{i2} + \ldots + n_{it-1} + \ldots. + n_{iT}\right)$$

The component $\frac{-y_{it}}{T-1}$ in the former is correlated with n_{it} in the latter, and the component $\frac{-n_{it-1}}{T-1}$ in the latter is correlated with y_{it-1} in the former. These are the leading correlations, which are both negative and which dominate positive correlations between the other components, so that the correlation between the transformed lagged dependent variable and the transformed error term can be shown to be negative. Hence, the within estimator will be biased downwards. However, in our case, where we have a relatively long panel (T is more than 20 years), we can expect that the strength of these correlations will be attenuated and, as a consequence, that the bias will not be as severe as in the growth rates model where the correlation between the lagged dependent variable and the transformed error is first order. We expect to have the true ρ in an interval where the right limit is OLS, the left limit is the growth rate (or the first difference model) and the within rho located in the middle. For the above mentioned reasons all three estimators will be biased; however, it is still possible to get consistent estimators by using instrumental variables (2SLS) or consistent and efficient estimators by using GMM.

Table 2.4 shows the results of estimating this dynamic knowledge production function (Autoregressive Distributed Lag model ADL) using the methods described above. The coefficient of the lagged dependent variable moves as we expected: it is very high in OLS and very low in the first difference model. The within (or fixed effects) transformation generates a higher value than the growth rate model and a lower value than OLS. The results in the last column apply the GMM (Arellano–Bond) method. Under this procedure we use the largest possible set of instruments in order to control for endogeneity and we also weight with an efficient covariance matrix. As can be seen from the table, the set of instruments is valid and the error does not show evidence of second order autocorrelation. Thus, the GMM (Arellano–Bond) method produces the most robust results. We find that the HERD long run elasticity is 0.64, which is higher than in the benchmark model.[7]

[7] The Arellano-Bond results shown in Tables 2.4 and 2.5 correspond to the one-step Arellano-Bond estimates with robust standard errors to deal with the problem of heteroskedasticity. One alternative

Table 2.4: Results using ADL Model (dependent variable log publications)

	OLS	First Difference	Within Groups	Anderson-Hsiao	Arellano-Bond
	Yit	Yit	Yit	Yit	Yit
$HERD_{it}$	0.028	0.038	0.036	0.078	0.061
	0.008***	0.06552	0.020*	0.063	0.024**
Non-$HERD_{it}$	0.000	-0.001	0.000	0.001	0.000
	0.200	0.230	0.200	0.330	0.170
Y_{it-1}	0.963	0.161	0.919	0.16	0.904
	0.008***	0.066**	0.019***	0.062**	0.023***
Year	-0.001	-0.001	0.001	0.028	0.000
	3.10(-4)***	3.10(-4)***	0.002	0.004***	0.200
Constant	2.251	2.565	-0.639		
	0.726***	0.767***	1.826		
Observations	294	280	294	266	280
Sargan-Test					0.0592
1st Autocovariance					-7.15
2nd Autocovariance					-0.62
Long Run Elasticity Domestic Knowledge	0.750	0.040	0.440	0.090	0.640
	0.073***	0.079	0.227**	0.076	0.233***
Years for 90% of effect	60	1	24	1	22

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

Table 2.5 shows the results for citations. They are similar to those obtained for publications with the autocorrelation coefficient moving within the expected ranges. The main difference here is the presence of much higher long-run elasticity for the stock of knowledge in relation to the citations output. This value is about 0.87 (for the GMM results).

It is worth analysing the lag structure implicit in this model. Using (9) and the results in Tables 2.4 and 2.5 it is possible to track the evolution of a given increase in the domestic HERD (stock of knowledge). As can be seen from Figure 2.3 the typical cost of adjustment mechanism (computed from the GMM results in Table 2.4) assumes an exponentially declining pattern of weights, which means that the greatest impact of a given increase in the domestic R&D is expected to be concentrated at the beginning of the time period. However, this lag pattern is very different from the pattern in the publication cycle of almost every other discipline. Therefore, assuming this lag structure does not seem to be appropriate for estimating the production of science, we need to develop a methodology that will allow us to validate the assumed

possibility was to use two-step standard errors, which should be more efficient in the presence of this problem. Unfortunately, in the context of the Arellano-Bond estimator, the two-step standard errors tend to be biased downwards in small samples. For this reason, the one-step results are generally recommended for inference. Similarly, the reported Sargan test originates from the one-step estimator, under the assumption of homoskedasticity (the distribution of the Sargan test with robust standard errors is unknown). Because the Sargan test over-rejects in the presence of heteroskedasticity, using the one-step homoskedastic results in a very conservative approach (see Arellano and Bond (1991) for details).

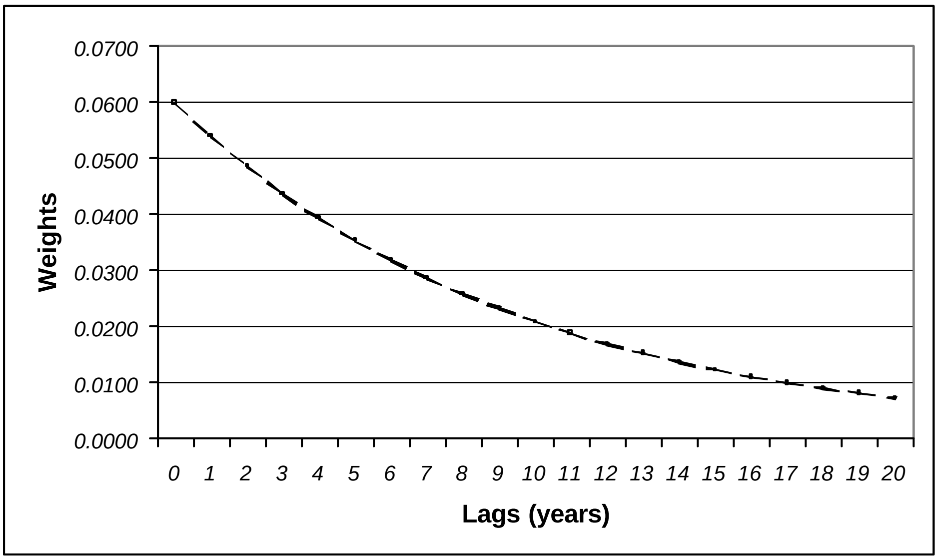
weights structure of this and the previous model. In addition to this the lags implied using this methodology look quite long: about 20 years for 90% of the impact of a $1 increase in the HERD.

Table 2.5: Results using ADL Model (dependent variable log citations)

	OLS	First Difference	Within Groups	Anderson-Hsiao	Arellano-Bond
$HERD_{it}$	0.052	0.064	0.052	0.089	0.096
	0.009***	0.108	0.027*	0.090	0.036***
$Non\text{-}HERD_{it}$	0.000	-0.003	-0.001	-0.002	-0.002
	0.002	0.005	0.001	0.004	0.002
Y_{it-1}	0.938	0.129	0.912	0.141	0.890
	0.009***	0.069*	0.018***	0.063**	0.023***
Year	-0.001	-0.001	0.000	0.032	0.000
	0.001	3.10(-4)**	0.001	0.006***	0.001
Constant	1.580	2.859	-0.120		
	1.046	1.103**	2.400		
Observations	294	280	294	266	280
Sargan – Test					0.3049
1st Autocovariance					-7.31***
2nd Autocovariance					-0.33
Long Run Elasticity Domestic Knowledge	0.830	0.073	0.59	0.100	0.870
	0.051***	0.126	0.289**	0.106	0.294***
Years for 90% of Impact	35	1	24	1	20

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

Figure 2.3 Pattern of Weights, ADL model (Publications)



2.4 The Polynomial Distributed Lag (PDL) Model

One (but not the only) way to search for both a lag length and structure is to apply the technique known as Polynomial Distributed Lag (PDL) or the Almon Model (see Green, 1993). The methodology can be applied to our case as follows. Let us define the following 'finite' distributed lag model:

$$y_{it} = a_i + \sum_{j=0}^{q} b_j r_{it-j} + g_i X_{it} + u_{it}, \quad i = 1,.....N \quad (13)$$

Although a model like (13) can in theory 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 fairly low order.

$$b_j = d_0 + d_1 j + d_2 j^2 + ...+ d_p j^p, \quad j = 0,.....q > p \quad (14)$$

The order of the polynomial, p, is usually taken to be quite low, rarely exceeding 3 or 4. By inserting (14) into (13), one can estimate a transformed model where the estimated coefficients are deltas that can be put back into (14) 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 standard procedure for determining first the length of the lags and then the degree of the polynomial function.

To search for the lag length we start by using a lag of 10 years and proceed reducing by one period down to 0. In each reduction we evaluate the information that is lost because we omit on additional lag with the one that is gained because we have more degrees of freedom in the estimation. We used the following three different information criteria to identify the optimum lag:

$$AIC = -2\ln L(\hat{q}_k) + 2k$$

$$SBIC = -2\ln L(\hat{q}_k) + k\ln n$$

$$ICOMP = -2\ln L(\hat{q}_k) + s\ln tr(I(\hat{q}_k)^{-1}/s) - \ln\left|I(\hat{q}_k)^{-1}\right|$$

where k is the number of parameters, n the sample size, $\hat{q}_k$ the parameter estimates, $I^{-1}(\hat{q}_k)$ the inverse of the Fisher information matrix and s= $rkI^{-1}(\hat{q}_k)$. The best model minimises the criterion.

Table 2.6: Unrestricted Polynomial Distributed Lag (PDL) Model Approach (Fixed Effects) Publications

	10	9	8	7	6	5	4	3	2	1	0
	Lpub	Lpub	Lpub	Lpub	lpub	Lpub	lpub	lpub	Lpub	Lpub	lpub
HERD	-0.104	-0.091	-0.085	-0.082	-0.076	-0.080	-0.104	-0.140	-0.157	-0.288	0.012
	0.121	0.119	0.116	0.115	0.114	0.114	0.116	0.124	0.132	0.137**	0.092
t-1	0.073	0.065	0.068	0.069	0.062	0.060	0.054	0.068	-0.009	0.366	
	0.145	0.146	0.145	0.145	0.144	0.146	0.151	0.157	0.158	0.140***	
t-2	0.030	0.040	0.041	0.039	0.043	0.040	0.052	0.000	0.326		
	0.138	0.139	0.139	0.138	0.138	0.139	0.145	0.140	0.115***		
t-3	0.103	0.103	0.098	0.098	0.094	0.097	0.043	0.306			
	0.131	0.131	0.131	0.131	0.130	0.131	0.132	0.102***			
t-4	0.046	0.043	0.047	0.045	0.051	0.021	0.265				
	0.117	0.117	0.117	0.116	0.116	0.112	0.084***				
t-5	0.113	0.114	0.107	0.109	0.092	0.236					
	0.104	0.104	0.103	0.102	0.102	0.073***					
t-6	0.073	0.067	0.073	0.067	0.145						
	0.082	0.083	0.082	0.083	0.058**						
t-7	0.065	0.070	0.051	0.079							
	0.070	0.071	0.072	0.057							
t-8	-0.029	-0.047	0.028								
	0.078	0.079	0.053								
t-9	0.006	0.076									
	0.104	0.067									
t-10	0.073										
	0.085										
Non-HERD	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.001	-0.001	-0.001	-0.001
	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.005	0.005
Year	0.015	0.016	0.017	0.017	0.018	0.020	0.023	0.027	0.030	0.034	0.036
	0.004***	0.004***	0.004***	0.004***	0.004***	0.004***	0.004***	0.004***	0.004***	0.004***	0.003***
Constant	-23.419	-24.887	-26.404	-27.013	-28.829	-32.605	-38.990	-45.803	-52.081	-57.875	-61.893
	7.865***	7.680***	7.603***	7.442***	7.349***	7.246***	7.105***	7.203***	6.829***	6.468***	6.153***
Observations	168.000	168.000	168.000	168.000	168.000	168.000	168.000	168.000	168.000	168.000	168.000
AIC	-428.68	-429.89	-430.97	-432.85	-433.81	-431.96	-424.1	-414.71	-403.33	-395.26	-386.47
SIC	-347.46	-351.79	-356	-360.99	-365.08	-366.36	-361.62	-355.35	-347.1	-342.15	-336.48
ICOMP	NA	-262.66	NA	-274.57	-280.22	-283.61	-281.24	-276.13	-271.02	-268.05	-262.88
HERD_LR	0.45	0.44	0.43	0.42	0.41	0.37	0.31	0.23	0.16	0.08	0.01
	0.098***	0.096***	0.096***	0.096***	0.096***	0.098***	0.099***	0.104**	0.100	0.096	0.092

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

Table 2.6 shows the results of this exercise for publications and Table 2.7 gives the results for citations. Both tables show the lag structure for each alternative model and present the values for the information criteria and the long run elasticity for domestic HERD in the last three rows. In the results for publications (Table 2.6) two information criteria have a minimum value of a 5-year lag, while the remaining criterion has a minimum of 6-year lag. Because of the potentially more serious consequences of omitting some relevant lag, we have decided to keep 6-year lags as the optimum lag length for publications.

Table 2.7: Unrestricted Polynomial Distributed Lag (PDL) Model Approach (Fixed Effects) Citations

Lag Num	*10*	9	8	7	**6**	*5*	4	3	2	1	0
	Lcit	lcit	Lcit	Lcit	Lcit	Lcit	lcit	lcit	lcit	lcit	lcit
HERD	-0.269	-0.257	-0.251	-0.243	-0.229	-0.237	-0.271	-0.328	-0.354	-0.546	-0.129
	0.166	0.165	0.162	0.161	0.156	0.156	0.159*	0.168*	0.178**	0.179***	0.115
t-1	0.092	0.084	0.087	0.089	0.074	0.070	0.060	0.082	-0.041	0.508	
	0.206	0.205	0.205	0.204	0.200	0.202	0.213	0.226	0.232	0.198**	
t-2	0.013	0.022	0.023	0.017	0.027	0.021	0.038	-0.041	0.477		
	0.168	0.167	0.166	0.166	0.166	0.167	0.179	0.176	0.161***		
t-3	0.170	0.171	0.165	0.166	0.156	0.162	0.082	0.485			
	0.158	0.158	0.158	0.158	0.157	0.159	0.161	0.124***			
t-4	0.088	0.085	0.089	0.086	0.097	0.044	0.407				
	0.133	0.133	0.132	0.131	0.132	0.127	0.105***				
t-5	0.129	0.130	0.123	0.128	0.089	0.352					
	0.118	0.118	0.117	0.116	0.121	0.085***					
t-6	0.102	0.096	0.102	0.084	0.264						
	0.101	0.103	0.102	0.104	0.075***						
t-7	0.114	0.119	0.100	0.182							
	0.090	0.092	0.093	0.075**							
t-8	0.025	0.008	0.084								
	0.102	0.104	0.069								
t-9	0.011	0.077									
	0.111	0.079									
t-10	0.070										
	0.086										
Non-HERD	-0.008	-0.008	-0.008	-0.008	-0.008	-0.008	-0.009	-0.010	-0.009	-0.010	-0.010
	0.005*	0.005*	0.005*	0.005*	0.005*	0.005	0.005*	0.005*	0.006*	0.006	0.006
Year	0.013	0.013	0.014	0.015	0.017	0.021	0.026	0.032	0.037	0.042	0.045
	0.005**	0.005***	0.005***	0.005***	0.005***	0.005***	0.005***	0.005***	0.005***	0.004***	0.004***
Constant	-18.836	-20.240	-21.787	-23.624	-27.831	-34.710	-44.219	-54.682	-64.647	-73.110	-78.685
	9.650*	9.161**	9.107**	8.993***	8.882***	9.005***	8.709***	8.822***	8.451***	7.802***	7.625***
Observations	168.000	168.000	168.000	168.000	168.000	168.000	168.000	168.000	168.000	168.000	168.000
AIC	-385.630	-387.070	-388.330	-389.450	-387.190	-379.670	-365.950	-349.340	-329.110	-317.450	-306.450
SIC	-304.410	-308.970	-313.360	-317.600	-318.470	-314.070	-303.460	-289.980	-272.880	-264.340	-256.470
ICOMP	-211.910	-219.300	-224.440	-230.040	-232.810	-229.720	-222.080	-210.100	-196.660	-190.980	-182.590
HERD_LR	0.543	0.533	0.522	0.508	0.477	0.411	0.316	0.198	0.082	-0.037	-0.128
	0.125***	0.121***	0.121***	0.121***	0.122***	0.130***	0.131**	0.139	0.133	0.122	0.115

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

Table 2.7 summarises the results for citations. According to one criterion the optimum lag length is 7 years, while for the other two it is 6. Again, taking a conservative approach, we have chosen the longer lag. It is interesting to compare both results in terms of the long-run elasticities implied by the sum of all the individual coefficients. In the case of publications, the long-run elasticity is 0.41 and is statistically significant, and for citations it is 0.51 and also significant. These elasticities are not so far from the ones obtained using the benchmark model. Additionally, in both models we find that the share variable is negative, although significant only for citations, while the time trend is positive and significant.

Assuming that we have been able to identify the right lag length we proceed by looking for the right polynomial function. We start by using 5^{th} degree function and then proceed by testing sequential unit reductions in the degree. The results are shown in the last 4 rows of Table 2.8, where we can accept the reduction from 5^{th} to 4^{th} and from 4^{th} to 3^{rd} but not lower. It is important to note that in order to keep the appropriate significance level in each step we have used a very low individual significance level. The choice of a 3rd degree polynomial function is therefore accepted for both publications and citations.

Table 2.8: Unrestricted PDL and Restricted Almon Models (Fixed Effects)

	Unrestricted Publications	Restricted Publications	Unrestricted Citations	Restricted Citations
HERD	-0.076	-0.017	-0.243	-0.032
	0.113	0.018	0.161	0.017*
t-1	0.062	-0.001	0.089	-0.021
	0.144	0.033	0.202	0.024
t-2	0.043	0.033	0.017	0.017
	0.139	0.020*	0.170	0.022
t-3	0.094	0.078	0.166	0.073
	0.131	0.013***	0.158	0.016***
t-4	0.051	0.109	0.086	0.124
	0.116	0.013***	0.130	0.012***
t-5	0.092	0.117	0.128	0.157
	0.102	0.017***	0.116	0.015***
t-6	0.145	0.085	0.084	0.158
	0.058**	0.015***	0.104	0.017***
t-7			0.182	0.111
			0.074**	0.014***
Non-HERD	0.000	0.000	-0.008	-0.006
	0.001	0.001	0.004*	0.003*
Year	0.018	0.018	0.015	0.012
	0.004***	0.003***	0.004***	0.003***
Constant	-28.829	-29.505	-23.624	-18.009
	7.354***	5.808***	8.982***	6.795***
Observations	168	168	168	168
HERD_LR	0.410	0.405	0.508	0.587
	0.096***	0.071***	0.121***	0.081***
Chi (for Constraints)		1.54	1.06	
Pol Degree		Critical		Critical
5 to 4	1.26	6.63	3.710	6.63
4 to 3	1.45	7.83	4.580	7.83
3 to 2	12.53**	8.97	27.87***	8.97
2 to 1	59.27***	10.06	98.05***	10.06

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

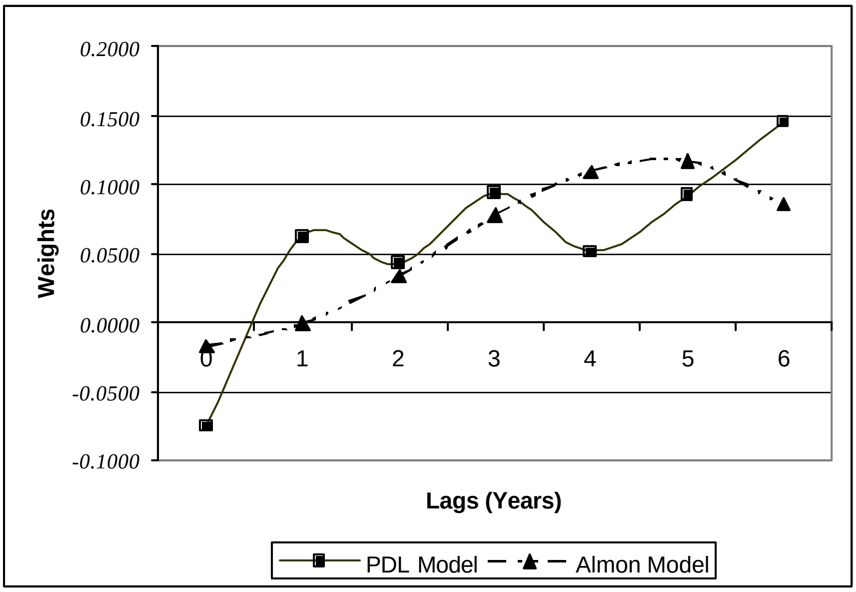
The PDL model also implies a set of constraints on the unrestricted model (without a specified functional form for the lags) estimated above. For example, if the optimum lag length is 6 and we use a 3rd degree polynomial function, we are implicitly imposing three constraints. In addition to this we have the 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[8] and also that there is no effect from the research inputs after the maximum lag. That is, we need to impose:

$$b_{-1} = 0 \qquad and \quad b_{q+1} = 0 \qquad (15)$$

In total we have five constraints. One way of validating the PDL model is by testing whether these constraints are valid. As shown by the Chi test in Tables 2.8, we could not reject any of them. In terms of the long-run elasticities we found that their values are very similar to those for the unrestricted model for publications and slightly higher in the case of citations. The time trend is positive and significant, while the non-HERD institutions have a negative effect on the citations only.

It is important to compare the unrestricted weights with the ones obtained using the restricted model. The pattern is similar for both publications and citations. The impact of the first two years is always very low and not significantly different from zero. It is only at the end of the 2nd year for publications (the 3rd year for citations) that we find the first positive impact. These impacts reach a peak at year 5 for publications (year 6 for citations).

Figure 2.4 Unrestricted vs. Restricted Pattern of Weights (Publications)



Figures 2.4 and 2.5 are graphical representations of the lag structure implied by the restricted (the dotted line) and the unrestricted models. What these figures clearly show is that only at the end of year 2 is it possible to see some positive impact from the investment in science. From the second year onwards, the returns from investment in science increase till the end of year 5 (or year 6 in the case of citations) and then decline till the end of year 6 (or year 7 for citations). Apparently, no significant returns can be expected after six years.

8 That means that the research output does not react 'in advance' of an increase in the research inputs.

Figure 2.5 Unrestricted vs Restricted Pattern of Weights (Citations)

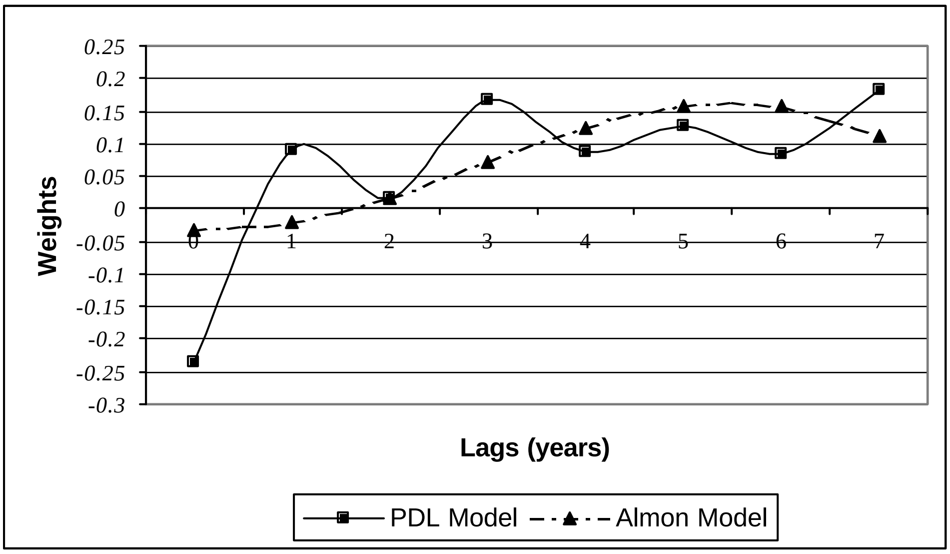
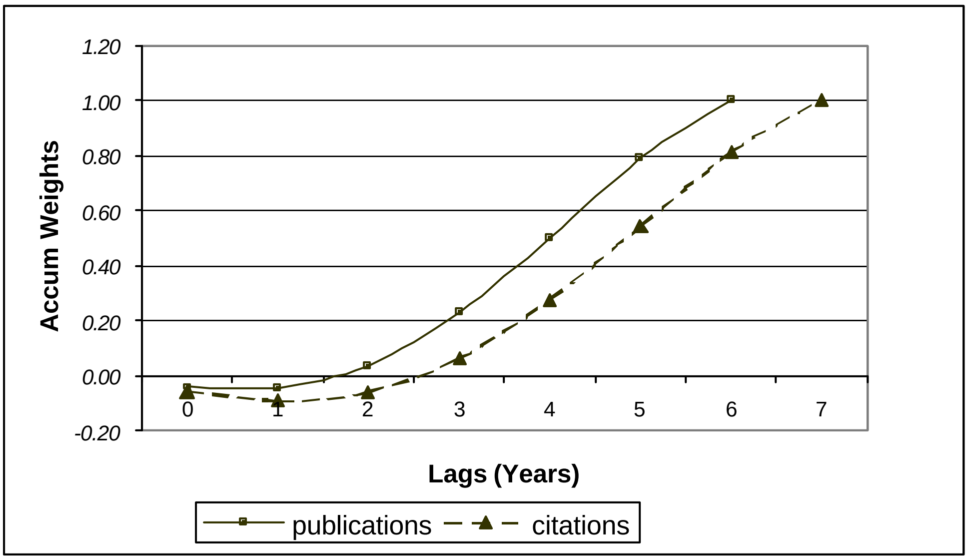


Figure 2.6 shows the evolution of the cumulative impact of HERD expenditure on scientific research outputs. In the case of publications, it is necessary to wait till year 4 (or year 5 in the case of citations) to gain 50% of the expected impact. We do not see any positive 'cumulative' impact until year 2 in the case of publications (year 3 in the case of citations).

Figure 2.6 The Cumulative Patterns of Weights (Publications and Citations)



The PDL model makes use of the lag structure of (the log of) past R&D. This implies a form of Cobb-Douglas knowledge-creation function where there is unit substitution elasticity between current and past R&D expenditures. It is important to say that this kind of function is slightly different to the one assumed in the benchmark model. Indeed, what Adams and Griliches used is the log of the weighted sum of past R&D. This implies a linear knowledge-creation function where there is a sort of perfect substitution between current and past R&D expenditures. Working with this sort of function in a context of panel data is very complex: it is not straightforward to cancel out the fixed effects by using either within or first difference transformations when the underlying function is not linear. Additionally, simply adding country dummies to the model makes the non-linear estimation process quite complicated. Having said that, we managed to calculate the non-linear estimate for the lag structure of publications. Both the optimum lag structure and the profile of the weights are similar to our previous linear estimations. Therefore, we decided to proceed with the simpler linear model.

2.5 The Search for Spillovers

In this section we investigate whether spillovers between countries are present. In this case, the term 'spillovers' means that part of the increase in the research output of a given country is due to the investment in HERD in other countries.

To the extent that an ever-growing external pool of knowledge available to each country generates these spillovers, the inclusion of a time-trend variable in the model partially capture these spillovers. As a consequence, we expect that the inclusion of a specific spillovers variable will not affect to a significant extent the estimated domestic HERD elasticity. However, the identification of a specific spillover effect allows us to calculate the total (domestic plus international) return to changes in the HERD investment for the system of countries considered.

In order to estimate the existence of spillovers, we need to assess the level of knowledge exchange or knowledge cooperation among countries. The higher the level of exchange/cooperation between countries *i* and *l*, the higher is the probability that some of the science investment in country *i* will affect the research output in country *l* and vice versa. To build up a matrix of knowledge proximity among countries, we have used the information on international scientific co-authorship. The NSF *Science and Engineering Indicators* reports (various years) give the share of cross-country co-authorships in the 1980s and 1990s. We have averaged the values and built a weight for each country as follow:

> w_{il} = number of international co-authorships between countries *i* and *l*, divided by the total number of international co-authorships carried out by country *l* with the other countries in the sample.

This weight provides a proxy for the relative knowledge exchange/cooperation between two given countries in our dataset. Table 2.9 presents the resulting weights for the 14 countries in our database. The US is the most important country for collaboration from all the countries considered (the US always has the highest weight). This indicates the special role played by the US in the process of knowledge creation. The table also clearly indicates how geographical proximity and cultural and linguistic links, which apply to Belgium and France, or to the UK and Australia, affect co-authorship patterns.

Table 2.9: Weighting Matrix

	AU	B	CA	Dk	Fin	F	D	I	NL	E	S	CH	UK	US
AU	0.000	0.012	0.087	0.017	0.007	0.051	0.088	0.025	0.028	0.008	0.031	0.024	0.214	0.409
B	0.011	0.000	0.035	0.015	0.014	0.192	0.118	0.065	0.120	0.035	0.036	0.050	0.107	0.201
CA	0.036	0.014	0.000	0.013	0.009	0.090	0.061	0.030	0.026	0.012	0.022	0.025	0.108	0.552
Dk	0.021	0.019	0.040	0.000	0.033	0.070	0.129	0.056	0.048	0.029	0.136	0.040	0.137	0.242
Fin	0.015	0.027	0.043	0.049	0.000	0.062	0.123	0.047	0.053	0.019	0.148	0.046	0.098	0.271
F	0.016	0.061	0.069	0.017	0.011	0.000	0.135	0.094	0.045	0.058	0.030	0.073	0.117	0.275
G	0.024	0.032	0.038	0.027	0.017	0.115	0.000	0.069	0.060	0.031	0.041	0.090	0.121	0.334
I	0.012	0.031	0.033	0.020	0.011	0.140	0.122	0.000	0.044	0.044	0.033	0.082	0.130	0.298
NL	0.019	0.080	0.041	0.025	0.018	0.094	0.148	0.060	0.000	0.029	0.036	0.049	0.147	0.255
E	0.007	0.036	0.028	0.021	0.009	0.186	0.114	0.093	0.043	0.000	0.024	0.040	0.156	0.241
S	0.024	0.029	0.040	0.083	0.061	0.075	0.118	0.053	0.042	0.020	0.000	0.042	0.114	0.300
CH	0.014	0.030	0.035	0.019	0.015	0.138	0.199	0.103	0.044	0.024	0.032	0.000	0.099	0.248
UK	0.056	0.029	0.068	0.028	0.014	0.098	0.118	0.072	0.059	0.041	0.039	0.044	0.000	0.335
US	0.053	0.026	0.171	0.024	0.018	0.113	0.162	0.082	0.050	0.032	0.050	0.055	0.165	0.000

Source: Weighting Matrix. Author's own elaboration based on NSF data.
Australia (AU), Belgium (B), Canada (CA), Denmark (Dk), Finland (Fin), France (F), Germany (G), Italy (I), Netherlands (NL), Spain (E), Sweden (S), Switzerland (CH), United Kingdom (UK) and United States (US).

After building these weights we define the 'international' research and development relevant to each country as a weighted sum of the science budgets of all the other countries as follows:

$$S_{lt} = \sum_{i \neq l} w_{il} R_{it} \quad (16)$$

where R_{it} is the HERD budget for country *i*. After constructing (16) we assume that the lag structure is same as in the previous section.[9]

The model estimated in this section focuses on long-run spillover effects. In order to compare these effects with the long-run impact of domestic R&D, we have redefined the stock of knowledge as a weighted sum of (the log of) R&D, where the weights are defined (as in Green, 1993) as follows:

$$w_j = \frac{b_j}{\sum_{j=1}^{k} b_j} \quad (17)$$

and we use the weight ω_j in order to aggregate the lag for (the log of) research and development expenditure for each country in the dataset. In this way we get rid of the need to estimate the short-run elasticities (which we assume to be known) and instead focus on long run elasticities.

[9] We do not have enough observations to search for a different lag structure for the spillover variable.

Table 2.10: Results using 6 (7) Lags of RD for Publications (Citations) plus Spillovers [dependent variable log Publications (Citations)]
Fixed Effects by Country Included

	Publications (1)	Publications (2)	Citations (3)	Citations (4)
Non-HERD$_{it}$	-0.005	-0.004	-0.013	-0.012
	0.001***	0.002**	0.002***	0.002***
Year	0.018	-0.000	0.014	-0.014
	0.002***	0.0020	0.003***	0.006**
HERD$_{it}$	0.475	0.447	0.536	0.499
	0.047***	0.045***	0.049***	0.047***
S$_{it}$		0.505		0.599
		0.116***		0.123***
Constant	-35.024	-2.859	-21.162	27.627
	4.444***	7.9410	6.187***	11.60**
Observations	224	224	210	210
R-squared	0.89	0.90	0.87	0.88
Test CRS (P-Values)	0.69		0.62	

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

The results of estimating this model are presented in Table 2.10 (for both publications and citations). The first column shows the estimated parameters without the spillover effects; these results are statistically equivalent to the ones in Table 2.8. When we include the variable S_{it}, which tries to capture the spillover effect, the magnitude of the long-run elasticity for HERD remains stable (dropping only marginally). Interestingly, the variable S_{it} is highly significant and has a large estimated parameter. In addition to this, the value of the time trend variable (Year) drops and is no longer significant. This validates our previous conjecture that the time trend was in some way capturing part of the spillover effect. In the case of citations (an impact adjusted measure of output) we obtain a positive and significant estimation for the spillovers. It is interesting to note that in this case the time trend is negative and significant. This result can be interpreted as indicating an overall negative trend in the production of science output once it has been adjusted for impact. So, if we consider citations as a proxy for 'quality' of science and not just impact, the model indicates an overall decrease in the 'quality' of the scientific output at the world level.

Another interesting result relates to the magnitude of the coefficients for both domestic HERD and international spillovers (S_{it}). Their sum is very close to that for publications and just above that for the citation estimates. These results suggest the presence of decreasing returns to scale at the domestic level,[10] but constant or perhaps even increasing returns to scale at the global level. However, the null of constant returns to scale at the world level was never rejected.

[10] The result of decreasing to scale at domestic level could have interesting implications for the analysis of long-term economic growth. This result is consistent with the work of Jones (1995) showing that there is no correlation between R&D investment and total factor productivity growth in the long run (although there is in the short run).

3 The Productivity Ranking.

A different way to assess the efficiency of a country is to evaluate the Total Factor Productivity (TFP) of scientific production. The TFP measurement was developed in the context of long-term economic growth accounting to account for the difference between measurable increases in inputs and outputs – to the extent that output increases exceeded the growth in inputs (e.g. of labour and capital), this increase was associated with an increase in TFP. In initial estimates by R. Solow, the contribution of TFP to economic growth was very large – later authors, especially D. Jorgensen, produced estimates that substantially increased the contributions of labour and capital by better recording quality changes in these inputs.

In the context of the scientific system, the TFP measure captures the overall organisational productivity of a scientific system that is not accounted for by increases in measurable inputs. Countries with the highest TFP are ones in which the 'boost' from other unmeasured factors lift the residual productivity of the scientific system above the increase that can be accounted for by increases in measured inputs. In other words, changes in the TFP of given country are the changes in the research output not explained by the changes in the input factors (in our case *the stock of domestic knowledge* as measured by the weighted sum of the lagged HERD investments and other control variables) that can be attributed to changes in overall organisational efficiency of the system.[11]

The traditional productivity index used many times in science policy has been the paper per $ of (current) HERD ratio. In the context of the present research we argue that this index is very incomplete proxy for research productivity for three main reasons. First, the simple ratio does not control for other factors that affect the research outputs such as the way in which the resources are allocated,[12] differences in the scientific opportunity and the effects of international knowledge spillovers. Second, the simple paper per $ of HERD ratio does not considers the right denominator. The input is *the stock of domestic knowledge*, not the current HERD. Given the important lags in the research process, the research output in a given time is the result of a sequence of HERD investments carried out from years ago. Indeed, it is highly likely that the current HERD is not related at all with the current (observed) output. This leads to the second drawback of the naive paper per $ of HERD ratio: it will be also strongly affected by the history of past investments in HERD by a given country. Finally, the paper per $ HERD ratio implicitly assume the existence of a linear relationship from input to output (the so-called constant returns to scale assumption). We have shown above that this is not true and that decreasing returns are more likely as a consequence the paper per $ HERD ratio will be also affected by the presence of scale effects, which means that one should be cautious when comparing nations with remarkably different volumes of scientific output. For instance, one cannot extrapolate in a simple, linear way the likely performance that low volume countries would experience if they were to increase their HERD expenditure, to compare them to high volume countries.

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[11] For example, differences in the rewarding or promotion systems for the researchers, or the introduction of new approaches to assess the research output.

[12] For example the relative importance of the other public and private research institutions not included in the Higher Education category which have lower efficiency in terms of publication or citation output.

Table 3.1: Productivity Ranking - Publications

Year	AU	B	CA	Dk	Fin	F	G	I	NL	E	S	CH	UK	US
1987	7	13	5	12	1	4	3	8	9	6	11	10	2	1
1988	7	13	5	12	1	4	3	8	9	6	11	10	2	1
1989	7	13	5	12	1	4	3	8	9	6	11	10	2	1
1990	7	13	5	12	1	4	3	8	9	6	11	10	2	1
1991	7	13	5	12	1	4	3	8	9	6	11	10	2	1
1992	8	13	5	12	1	4	3	7	9	6	11	10	2	1
1993	8	13	5	12	1	4	3	7	9	6	11	10	2	1
1994	8	13	5	12	1	4	3	7	9	6	11	10	2	1
1995	8	13	5	12	1	4	3	7	9	6	11	10	2	1
1996	8	13	6	12	1	4	3	7	9	5	11	10	2	1
1997	8	13	6	12	1	4	3	7	9	5	11	10	2	1
1998	8	12	7	13	1	4	3	6	9	5	11	10	2	1
1999	8	12	7	13	1	4	3	6	9	5	11	10	2	1
2000	8	12	7	13	1	4	3	6	9	5	10	11	2	1
2001	8	12	7	13	1	4	3	6	9	5	10	11	2	1
2002	7	12	9	13	1	4	3	6	8	5	10	11	2	1

The TFP approach allows us to overcome the problems with simple paper per $ of HERD ratio. We compute it as follows: we first add the current and past HERD using as weights the same coefficients estimated in the previous section, this produce a proxy for domestic stock of knowledge. Second, the stock of knowledge is weighted by the long run elasticity, eliminating the scale effects. Finally, after estimating the productivity per stock of knowledge we also control for the effects of resources allocation (through the importance of Non-Herd institutions in the total GERD) and international spillovers of knowledge.

The literature on efficiency analysis suggests that it is possible to use the TFP as defined above to evaluate efficiency in terms of the relative performance of the different scientific systems at country level. More precisely, it is possible (a) to produce rankings from the most efficient to the least efficient country and (b) to follow country-specific efficiencies over time in order to determine the presence (or absence) of a catching-up process (in terms of efficiency). The frontier of ‘scientific productivity’ can be defined across countries by identifying the country with the highest TFP. We calculated it with a stochastic frontier approach.[13] This frontier provides a basis for ‘ranking’ other countries (with lower TFP) against the leader, and the leader against its ‘optimal productivity’ over time. Over time, we can study the changes in the technological efficiency of a country (did the country move nearer or further away form the frontier?). This measure gives an idea of the changes in the relative scientific productivity of a country, which depends on the organisation of the scientific system of that country.

[13] For a detailed description of this methodology see Coelli et al. (1998).

Table 3.1 shows the results of the relative productivity ranking for publications. From this table it is clear that the four largest countries dominate with the US in first place and the UK in second place, followed by Germany and France. This finding confirms the conventional view that the UK is one of the most productive countries in the world. While the top part of the ranking is quite stable over time, there is some mobility in the mid to bottom half of the rankings. For example, Italy moves up three positions, while Spain, Sweden, the Netherlands and Belgium each move up one place. Some countries, such as Canada, Denmark and Switzerland, move down the rankings.

The estimates presented in Table 3.1 are affected by the problems with the HERD data discussed in the introduction, especially those relating to cross-country comparability. Consequently, we decided to present only the efficiency ranking and not the estimated parameters. However, even the ranking cannot be considered robust as different results were obtained using different estimation techniques. On the other hand, the change in relative efficiency at country level (how does the distance from the efficient frontier vary during the 16 years considered) is not affected by the comparability data problem and, therefore, is more reliable. The productivity ranking (not to be considered robust) was presented above as a way of introducing the much more robust analysis of relative productivity changes, which allows us to discuss the catching up by countries in terms of scientific productivity.

Table 3.2: Changes in Relative Productivity: Publications

	Growth	SE	Constant	SE	Observations	R-squared
AU	-0.004	0.002**	2.165	0.017***	16	0.28
B	0.007	0.002***	1.730	0.016***	16	0.53
CA	-0.030	0.001***	2.557	0.010***	16	0.98
Dk	0.004	0.002*	1.768	0.0192***	16	0.19
Fin	0.012	0.002***	1.600	0.027***	16	0.54
F	0.004	0.002**	2.578	0.015***	16	0.26
G	0.001	0.002	2.672	0.0157***	16	0.02
I	0.013	0.001***	2.080	0.016***	16	0.79
NL	0.000	0.010	2.092	0.019***	16	0.01
E	0.011	0.002***	2.155	0.020***	16	0.66
S	0.013	0.002***	1.782	0.026***	16	0.61
CH	-0.001	0.002	1.963	0.015***	16	0.02
UK	-0.005	0.002**	3.061	0.019***	16	0.29
US	-0.025	0.001***	4.396	0.007***	16	0.99

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

The rankings do not tell us very much about the dynamic process governing the changes in the relative positions of countries. In order to improve on this we compute the relative productivity growth rate of each country individually and then compare growth rate figures. Several interesting results emerge from Table 3.2. First, all countries except the US, Australia, Canada and UK have positive productivity growth rates (Switzerland shows an apparent decrease in productivity, but it is not significant). This means that all countries are converging towards the 'efficient frontier' of the US. Second, the convergence of the UK towards the US is mainly due to a deterioration in US productivity: the UK relative productivity growth rate also declines over the period, but at a slower pace than US productivity. Third, the other countries are catching up to the UK because (with the exception of Canada) they exhibit a positive or zero growth rate or one that is decreasing less rapidly than the UK productivity growth rate.[14]

We repeated the analysis for the case of citations. The results are qualitatively the same, although in this case there is much more mobility in the lower tail of the distribution (see Table 3.3). The fall in the case of Australia and Canada is larger and there is a clear improvement in the case of Denmark, Italy and Spain. However, the biggest countries maintain their dominant positions. The UK is still the second most efficient country in the 'world'. The results for citations in terms of catching up are also the same (see Table 3.4).

Table 3.3: Productivity Ranking, Citations

Year	AU	B	CA	Dk	Fin	F	G	I	NL	E	S	CH	UK	US
1987	8	14	3	9	13	4	5	11	7	12	10	6	2	1
1988	8	14	4	9	13	3	5	11	7	12	10	6	2	1
1989	8	14	5	9	13	3	4	11	7	12	10	6	2	1
1990	8	14	6	9	13	3	4	11	7	12	10	5	2	1
1991	8	14	6	9	13	3	4	11	7	12	10	5	2	1
1992	9	14	6	8	13	4	3	11	7	12	10	5	2	1
1993	9	14	6	8	13	4	3	11	7	12	10	5	2	1
1994	9	14	6	8	13	4	3	11	7	12	10	5	2	1
1995	9	14	6	8	13	4	3	11	7	12	10	5	2	1
1996	9	14	7	8	13	4	3	11	6	12	10	5	2	1
1997	11	14	7	8	13	4	3	10	6	12	9	5	2	1
1998	12	14	8	7	13	4	3	9	6	11	10	5	2	1
1999	13	14	8	7	12	4	3	9	6	11	10	5	2	1
2000	13	14	11	7	12	4	3	8	6	10	9	5	2	1
2001	13	14	12	7	11	4	3	8	6	10	9	5	2	1
2002	12	14	13	7	11	4	3	8	6	9	10	5	2	1

Whether the catching up (or falling behind) results represent a 'real' relative productivity increase (or decrease) or whether they are 'contaminated' by the fact that those countries that are catching up are increasingly publishing in journals included in

[14] Borrowing from the economic growth literature our definition of convergence here is close to what has been termed *beta convergence* (see Sala-i-Martin (1996) for details). In the economic growth context, this concept refers to a negative coefficient when the growth rate of our measure of efficiency (the residual of the production function) is regressed on past levels of efficiency. We also did this here by running a regression such as $\Delta \ln(A_t) = a + b \ln A_{t-1}$; we obtained a beta coefficient of –0.0108 with a significant t test of –2.94. This result implies that countries with the lowest efficiency in the past exhibit higher efficiency growth rates, implying convergence in levels. The second concept of convergence used in the literature of economic growth refers to what is called *sigma convergence*. This idea refers to a lower spread in efficiency levels across countries between two consecutive time periods. This sort of convergence is also verified: the initial standard deviation in the efficiency levels in 1987 was 0.70 while its value in 2001 was 0.60 and the decline was smooth across the period.

the ISI Current Content archive, is an open debate. Our results probably indicate that the latter possibly applies because only the English-speaking countries show significant negative relative productivity growth rates. This is exactly what would be expected from a diffusion process in which countries are publishing more and more frequently in English journals and, in particular, those on the ISI Current Content list.

However, it is interesting to note that Switzerland and The Netherlands also show some indication of falling behind (although this is only weakly statistically significant in the case of citations). These two countries, together with the English-speaking countries, are characterised by scientific systems with higher mobility, and by higher competition levels; they were also first to develop systems for increasing the research productivity of scientists (such as the Research Assessment Exercise). What our results may also indicate is that, given the fact that the 'technology' to produce scientific output has not radically changed,[15] the increase in scientific productivity has an upper limit. After a first positive phase the policies aimed at increasing productivity have ceased to produce results, while the countries that in more recent years developed policies to create incentives to increase the productivity of scientists, are now catching up.

Table 3.4: Changes in Relative Productivity: Citations

	Growth	SE	Constant	SE	Observations	R-squared
AU	-0.009	0.002***	2.165	0.022***	15	0.42
B	0.013	0.002***	1.730	0.016***	15	0.69
CA	-0.033	0.001***	2.557	0.015***	15	0.96
Dk	0.008	0.001***	1.768	0.010***	15	0.64
Fin	0.020	0.0045***	1.600	0.030***	15	0.59
F	0.005	0.002*	2.578	0.021***	15	0.19
G	0.019	0.001***	2.672	0.010***	15	0.95
I	0.013	0.002***	2.080	0.018***	15	0.71
NL	-0.005	0.002*	2.092	0.019***	15	0.21
E	0.018	0.003***	2.155	0.033***	15	0.61
S	0.009	0.003***	1.782	0.020***	15	0.39
CH	-0.006	0.002**	1.963	0.014***	15	0.34
UK	-0.008	0.001***	3.061	0.009***	15	0.75
US	-0.032	0.001***	4.396	0.011***	15	0.98

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

Finally, the countries that seem to be falling behind in terms of their scientific productivity are also the countries that had early and more actively developed policies for encouraging technology transfer activity in universities. These countries are among the first to have developed policies to foster, for example, university-industry linkages or university patenting activity; one might speculate whether, as result of increased activity in the technology transfer area, universities have been less productive in their more traditional activity of scientific publishing.

[15] The diffusion of Information and Communication Technologies may have improved the productivity of science, but it cannot be considered a significant change in the way researchers do research and write articles.

Econometric macro analyses, like those conducted in this report, cannot discriminate among the various possible interpretations of the macro trends. However, they provide strong empirical evidence of a specific phenomenon, such as the falling behind of the UK (relative to the other large European countries, but not relative to the US) in terms of scientific productivity, which requires microanalysis if it is to be explained. Interestingly, much of the descriptive statistical literature on UK science productivity has failed to identify the falling behind phenomenon because of the lack of a time lag component and the failure to adopt a multivariate approach in its analyses.

4 Graduate Students as Output of Research Spending.

In this section we carry out an exploratory analysis of the human capital formation component of research output. We study the relationship between investment in HERD and output of graduate students. Is the investment in university research affecting the number of PhD students produced by a country?

As was discussed in the introduction, published research is only one of the outputs of the research activities carried out by higher education institutions. The training of research students during their PhD programme is intertwined with the research carried out in the institution. Some knowledge is transferred from university research to society via the education of PhD students. Students increase their human capital in the course of carrying out research with their supervisors. This transfer of tacit knowledge in the form of increased human capital of graduating PhD students is considered by many as one of the most important results of the research carried out in higher education institutions (Salter et al., 2000).

The analysis in this section is by definition exploratory because information about the numbers of PhD degrees awarded as collected by the OECD is relatively new and covers only the last 3 years of the sample period.[16] Because of information constraints, we cannot analyse distributed lag structure and hence we take the lag identified for publications as given.[17] However, the most important limitation is that we may not have enough within-country variation to exploit the idiosyncratic characteristics of the panel data. We have estimated the model using two panel data approaches. Fixed Effects, which remove all cross-country variations and focus only on the within-country variation, and Random Effects, which keep the cross-country variations, but use a much more efficient method of estimation. In order to see which approach is the more appropriate, we carried out the Hausman test.

The results of this test are presented in Table 4.1 where, if we look at the final row, we can infer that the fixed effect model is rejected in favour of the most efficient random effect.[18] The random effect results suggest that there is a very strong correlation between the research budget and the 'production' of graduates. The results

[16] We refer specifically to the ISCED level 6 (Advanced Research Programmes) graduates by country.

[17] We do not think that this is a serious shortcoming because many research programmes are quite long (4 to 5 years). Also many of the outputs of the research carried out as part of the degree are also associated with producing publications.

[18] We did the same test for all the previous models, establishing the fixed effect model as the best specification. The short time period available for the human capital data is probably the main reason for a different result being obtained.

also indicate a long-run elasticity close to 1, leading to the conclusion of constant domestic returns to scale.

Table 4.1: Results for Teaching Research Output.

	Log(students) Fixed Effect	Log(students) Random Effect
Non-$HERD_{it}$	-0.035	0.012
	0.038	0.022
Year	-0.026	0.022
	0.048	0.027
$HERD_{it}$	2.778	0.989
	1.45*	0.137***
Constant	40.968	-43.219
	87.166	51.451
Observations	40	40
Number of Countries	14	14
R-squared	0.24	0.18
Fixed vs Random Effect		
Hausman Test		2.36
P-Value		(0.5009)

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

5 Sources of Science Funding: A preliminary look at the 'crowding in' (or 'crowding out') phenomenon.

Funds for R&D in the HE sector come from many sources. The main source has traditionally been the public-funded block-grant known as public general university funds (GUF) which HE institutions receive to support all their activities. In addition, R&D funds are received in the form of grants or contracts from such sources as ministries, departments and other public institutions, including research councils and, increasingly in recent years, private non-profit institutions, from industry and from abroad.

It is important to study the relationships between the different sources of funds in order to examine whether there are complementary or substitution effects. That is, it is not possible to guarantee that a given increase in government funds to R&D is going to be linearly transmitted to the university research budget: the presence of a 'crowding in' (or 'crowding out') phenomenon in relation to other available research sources must be taken into account. For example, there are situations when there is positive correlation between private and public resources for university R&D; for instance, public resources can be used to finance fixed capital costs (such as the building of laboratories), allowing the university to price at variable cost research services to the business sector.[19] Public resources can be used to fund the riskier

[19] Public funding to universities does not necessarily mean the funding of research projects; there is a lot of infrastructure funding. The presence of this sort of funding clearly reduces the possibility of the crowding out effects and increases the margins for complementary effects.

component of the research project (i.e. the basic research) and then private funds can be used to complete the development phase of the research project. However, the relationship might also lead to a substitution effect. This would occur in situations where the type of project being funded by research councils was very similar to the types of projects funded by firms, or, more indirectly, when the distortions introduced by the tax system in order to collect the additional resources for funding public R&D reduce the private returns to investment (in general, and in particular to R&D).

A similar set of conjectures can be made about the relationships between public R&D and other (non-profit) sources of funds. If the public funded projects are based on a matching-grant policy only, we could expect a 'crowding in' type of effect. However, if there is an overlap in the portfolio of research projects being funded by these two sources, this might produce a form of displacement. The issue here is that it is not possible to fully understand the effects of a given increase in public funding of R&D on the different research outputs without taking account of these various relationships.

The existing literature has mainly focused on the impact of public subsidies on the research output or research expenditures of the firm (Hall and David, 2000); it is mainly concerned with business research and it cannot be straightforwardly applied to scientific and academic research. However, there are some issues that apply to both areas. As we suggested above, the subsidies given by a research council to an individual researcher or research team can be seen as affecting the relative rewards from research compared with other activities such as teaching. From the individual's point of view therefore, receiving a subsidy may turn an unprofitable project into a profitable one. Alternatively, it may speed-up the completion of a project already underway. If research council subsidies involve setting up or upgrading research facilities, then this will reduce the fixed costs of other current and future research projects, increasing their probability of being completed or undertaken. Also, the learning and know-how gained from the project being supported can spill over to other current and future research projects, thereby enhancing their prospects for success. In all these ways, a research subsidy may stimulate current and future research projects. If these hypotheses are true, we can expect a positive impact from the public component of the Science Budget on the other sources of funds.

However, there is empirical evidence suggesting that some research projects can be carried out in the absence of government funding. There are several external sources of funds for research proposals including public foreign or multilateral institutions (such as the EU, NSF, etc.), the business sector and charities. This possibility of substitution can be increased by administrators who are often under pressure to avoid the appearance of 'wasting' public funds and who may tend to fund projects with a higher success probability and with clearly identifiable results (projects that are likely to have a range of alternative sources of funds). These are projects that could have been financed by other sources of funds, suggesting that the public funds can in fact be superfluous.

Another reason for substitution is that a project enhanced by a subsidy has an effect on the price of the inelastically supplied research time (no one can work more than 24 hours a day). If the subsidy turns an unattractive project into an attractive one, but there are time constraints, the researcher or the team may decide to discontinue what previously was an attractive project (which might have been funded by other sources of funds). The commitment to undertake the subsidised project may crowd-out other non-subsidised projects (and their accompanying resources). Thus, we cannot simply extrapolate that a given increase in public funds to the university research budget will lead immediately to a proportional increase in the global research budget. We need to investigate the effect on the other sources of funds.

We can position this analysis clearly in term of an accounting framework (for details, see Lach, 2001). Let us assume that the size of R&D projects is fixed. The only decision the researcher makes is whether or not to undertake the project. Each researcher has n potential projects, each of size α_i, i=1,...,n. Then the total research projects of a researcher is given by:

$$R^0 = \sum_{i=1}^{n} a_i c_i^o \quad (18)$$

where c_i^0 is a binary variable indicating whether the project i is undertaken or not if a subsidy is not received. Assume that the researcher applies for a subsidy only for the n_{th} project. Then the research budget 'with' the research council support is:

$$R^1 = \sum_{i=1}^{n} a_i c_i^1 \quad (19)$$

Note that receiving the subsidy can change the decision to undertake any of the first (n-1) projects and that the subsidised project (project n_{th}) is always implemented, $c_n^1 = 1$, because of the contractual agreement. Then the increase in the researcher's budget as a consequence of receiving research council funding is:

$$\Delta = R^1 - R^0 = \sum_{i=1}^{n-1} a_i (c_i^1 - c_i^0) + a_n (1 - c_n^0) \quad (20)$$

In order to evaluate the potential impact of the public subsidy, suppose first that the subsidy does not change the decision about the unsupported projects, $c_i^1 - c_i^0 = 0$ for i=1,....,n-1. Then,

$$\Delta = \begin{cases} a_n & if \quad c_n^0 = 0 \\ 0 & if \quad c_n^0 = 1 \end{cases} \quad (21)$$

Clearly Δ is positive only when the subsidy causes the subsidised research project to be implemented and Δ is zero if the subsidised project would have been undertaken even in the absence of the subsidy. When the decision to implement the other non-subsidised projects can change as a result of receiving the subsidy, the consequences are not so clear. Without loss of generality, let us assume that only the decision about the $(n-1)_{th}$ project can change. We then have several possibilities:

$$\Delta = \begin{cases} (1)\ a_{n-1} + a_n & if \quad c_n^0 = 0 \quad \& \quad (c_{n-1}^1 - c_{n-1}^0) = 1 \\ (2) - a_{n-1} + a_n & if \quad c_n^0 = 0 \quad \& \quad (c_{n-1}^1 - c_{n-1}^0) = -1 \\ (3)\ a_{n-1} & if \quad c_n^0 = 1 \quad \& \quad (c_{n-1}^1 - c_{n-1}^0) = 1 \\ (4) - a_{n-1} & if \quad c_n^0 = 1 \quad \& \quad (c_{n-1}^1 - c_{n-1}^0) = -1 \end{cases} \qquad (22)$$

The gain in terms of the global research budget is positive when both projects are implemented as a result of receiving the subsidy, as in case (1) of equation 22. This is the best result: the subsidy makes attractive not only the subsidised project, but also a non-subsidised one. This may happen when the subsidised project involves the setting up or upgrading of research facilities, thereby lowering the costs of other current (and non-subsidised) research projects.[20] There may also be spillovers of learning and know-how gained from the subsidised project to other current (and future) research projects, thus increasing their attractiveness.

On the other hand, the opposite effect may occur when the time constraints are severe and this reduces the attractiveness of project $(n-1)_{th}$. The researcher or the research team may find it more attractive to discontinue the non-subsidised project (case 2). Then the researcher's total research budget may decrease or increase as a result of the subsidy depending on the relative amounts of resources awarded to each research project.

Cases (3) and (4) involve situations where the subsidised project would have been undertaken even without subsidy ($c_n^0 = 1$). In this respect, the subsidy is superfluous and does not contribute to the research budget at all. If, however, the funds released by the subsidy are used to implement an additional project which could not have otherwise been undertaken, then the subsidy effect becomes positive (case 3). The last case is when the $(n-1)_{th}$. is closed down ($c_{n-1}^1 = 0$) as result of receiving the subsidy (case 4) and in this instance the researcher's budget will decrease. The main conclusion of this analysis is that the impact of public subsidies on the other sources of funds is not an obvious one and that in order to determine the impact we have to look not only at the total, but also at the components of the research budget.

We start with the following model:

$$r_{it}^B = q_i + \sum_{t=0}^{q} a_t r_{it-t}^G + l_t + h_{it} \qquad (23)$$

where $r(B)_{it}$ is the (log of the) total research budget coming from the business sector and $r(G)_{it}$ is the public component of the research budget. From the discussion above it becomes clear that the relationship between public investment in R&D and the other sources of funds is dynamic, being the reason for choosing a dynamic specification in Equation 3.5. In order to demonstrate this, let us define J_{it} as representing the

[20] For example, the subsidised project might include collecting a large dataset that can be drawn on for other papers or publications (non-subsidised).

unobserved know-how and R&D reputation of a given research system which is part of $h_{it}, h_{it} = J_{it} + e_{it}$ where e_{it} is a true identically and independently distributed idiosyncratic zero mean shock and J_{it} is determined in part by past R&D expenditures as follows,

$$E(J_{it} \mid r_{it-1,......}) = \sum_{t=1}^{p} b_t r_{it}^{G} + \sum_{t=1}^{p} g_t r_{it}^{B} + \sum_{t=1}^{p} d_t r_{it}^{O} \quad (24)$$

assuming that p=q , we have the following expression:

$$r_{it}^{B} = q_i + \sum_{t=0}^{q} (a_t + b_t) r_{it-t}^{G} + \sum_{t=1}^{q} g_t r_{it-t}^{B} + \sum_{t=1}^{q} d_t r_{it-t}^{O} + l_t + e_{it} \quad (25)$$

where $\beta_\tau=0$ when $\tau=0$ and $r(O)_{it}$ is the log of other sources of funds, which in our case includes: higher education own funds, overseas funds, funds from charities and other private non-profit organisations. The coefficients of $r(G)_{it}$ reflect two types of subsidy effects: the direct effects of the subsidy mentioned above and the indirect effects operating through the know-how and reputation acquired during previous R&D. As is usual in this kind of model, the idiosyncratic term is assumed to be uncorrelated with the current and lagged variables in the model and therefore e_{it} is also uncorrelated with the lagged private, public and other sources of funds.

$$E(e_{it} \mid r_{it-1,.....}^{G} r_{it-1,.......}^{B} r_{it-1}^{O}) = 0 \ for \quad t \geq 2 \quad (26)$$

Taking first differences in (3.7) to get rid of the country-specific fixed effect results in the estimation model:

$$\Delta r_{it}^{B} = \sum_{t=0}^{q} (a_t + b_t) \Delta r_{it-t}^{G} + \sum_{t=1}^{q} g_t \Delta r_{it-t}^{B} + \sum_{t=1}^{q} d_t \Delta r_{it-t}^{O} + \Delta l_t + \Delta e_{it} \quad (27)$$

least squares techniques will be inconsistent because the $r(B)_{it-1}$ and ε_{it} will be correlated. The identifying assumptions in (3.8) guarantee that different sources of funds lagged for two or more periods can serve as valid instruments. The validity of all these instruments rests on the assumption that e_{it} is serially uncorrelated. The estimation technique for this model will be the standard GMM proposed by Arellano and Bond (1991). It is important to note that a similar equation can be estimated for the other sources of funds.[21]

[21] This approach to investigating substitution vs. complementing effects among the different sources of funds for R&D is not new and there has been some previous research on this topic regarding private spending on R&D by companies and tax credits or grants (see Lach (2001) and Hall and David (2000) for further details). What is new is the application of this framework in the context of university research – a context that is much more complex given the multiple sources of funds involved. It is important to clarify that the standard analysis of different sources of funds has focused on estimating Cobb-Douglas type knowledge production functions where the inputs (the explanatory variables) are divided between different sources of funds (see Adams and Griliches (1996) and Guellec and Potterie (2001)). We did not follow this approach here because we aim to answer a different research question.

Before describing the results we should add a comment. We are working with very aggregated data. If there are problems in just comparing total HERD among countries, such problems will be exacerbated when working with the different sources of funds that feed into the HERD. It is true that a first difference technique will help to make the situation more comparable because it gets rid of many systematic differences between the countries. However, it is well known that a first difference approach will increase the influence of measurement error in the time dimension of the series. Because of this, the following results should be viewed with caution and, rather than providing a precise estimate of the coefficients, they should be considered as an example of what can be done. Better information at country level is necessary in order to obtain more robust conclusions about the interactions.[22]

Table 5.1 shows the results of the GMM estimates corresponding to model (27). Although the results of the specification tests on both sources of funds are satisfactory and the statistical properties of the model are as expected, many of the short-run impacts are not significant. Because of this, we have also included the long run elasticities (which correspond to the accumulated values divided by one, minus the accumulated value of the autoregressive coefficients on each equation); the results suggest the presence of a *crowding in* impact of government R&D on business finance to HERD (0.96) and a very high *crowding out* effect on other sources of funds (-2.0). However, while the first result is not statistically significant, the second is only marginally significant. On the other hand, the results predict that other sources of funds and business finance are complementary.

The results presented in table 5.1 correspond to the structural coefficients. In order to get an indication of the final results, we need to introduce the fact that there are interrelationships among the different sources of funds. Thus, the last two columns of Table 5.1 shows the 'reduced form' coefficients where the focus is on only the relationship between government R&D and each of the other sources of funds. The long-run results suggest that a unit increase in total government spending will have a net impact on the business contribution to R&D of 0.57 units.[23] This reduction in the reduced form coefficient is because there are two opposites forces at work here: first, the increase in government spending will increase the business contribution (a direct impact), but, on the other hand, this will reduce the contributions from other sources of funds and these other sources of funds are complementary to business funds (an indirect impact). At the same time, the net impact of government spending on the other sources of funds will be a very high crowding out of –1.45. However, neither of these results is statistically significant.

What we want is to have a clear idea of the crowding in (out) effects among the different sources of funds in order to come up with an expected figure for the changes in the total research budget after a change in the public component has been introduced. Although it is possible to use a production function framework to investigate substitution effects, this requires estimating a much more complex production function (at least a CES type one).

[22] In practice we could not include Spain and Belgium due to inconsistencies in the data. See Geuna, (2001) for details.

[23] This result suggests a complementary effect between the public and private funding to HERD. These same sorts of complementing effects at the firm level have been reported by Lach (2001) and Hall and David (2000).

Table 5.1: The Relationship among the Sources of Funds: GMM Results

	Business Funds	Other Funds	Business Funds	Other Funds
	Structural M	Structural M	Reduced M	Reduced M
r(G)t.	0.378	-0.577	0.316	-0.627
	0.250	0.269**	0.243	0.272***
r(G)t-1.	-0.511	0.838	-0.428	1.003
	0.381	0.408***	2.253	0.407***
r(G)t-2	0.309	-0.427	0.225	-0.563
	0.377	0.407	0.357	0.402
r(G)t-3	-0.033	-0.145	-0.038	0.003
	0.254	0.279	0.253	0.300
r(B)t-1.	1.180	0.141	1.171	
	0.071***	0.077*	0.064***	
r(B)t-2	-0.418	-0.118	-0.382	
	0.099***	0.108	0.087***	
r(B)t-3.	0.089	0.065	0.079	
	0.066	0.076	0.061	
r(O)t-1	-0.019	1.117		1.188
	0.073	0.076***		0.069***
r(O)t-2	0.096	-0.263		-0.330
	0.104	0.112**		0.10**
r(O)t-3	-0.036	-0.003		0.019
	0.072	0.100		0.068
Observations	252	252	252	252
Number of Countries	12	12	12	12
Sargan Test	215.73	186.46	218.15	183.6
1st Autocovariance	-8.27 ***	-9.53***	-8.25***	-9.62***
2nd Autocovariance	0.09	1.12	0.14	-1.00
Long Run Elasticity G	0.967	-2.08	0.568	-1.455
	1.043	1.140*	1.119	1.297
Long Run Elasticity B		0.584		
		0.315*		
Long Run Elasticity O	0.280			
	0.214			

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

Considering these results as general trends, we can try to resolve the question about the final impact of a given X% in the government funding to the SEB. This is given by:

$$\Delta S\hat{EB} = \Omega_G \Delta r_{it}^G + \Omega_B \Psi_{B,G} \Delta r_{it}^G + \Omega_O \Psi_{O,G} \Delta r_{it}^G \quad (28)$$

where the Ωs represent the importance, or weight, of each of the funds from each source in total HERD and the Ψs are the corresponding elasticities. What is clear from

(28) is that a given X% increase in government spending will be translated into the same increase in the total SEB budget only if the corresponding partial elasticities capturing complementarities or substitution effects among the sources of funds (the ψ's) are equal to one. From the above results, it is clear that some elasticities are far from this value.

Table 5.2 presents an example of the crowding in or crowding out effect of an increase of X% in government spending in the UK. The SEB financing structure in the UK suggests a distribution where in 2000 government funding represents about 65% of the total (the value was 81% in 1981), and the business share is relatively small - 7% (growing from about 3% in 1981), while the growth of other sources is important (accounting now for 28% of the total budget, up from 16% in 1981). The combination of all these figures with the above mentioned elasticities will lead to the conclusion that an increase of X% in the total government budget will increase the Science Budget by only 0.279 of this value if we consider the reduced form model elasticities to be significant. If instead we use a more statistically valid approach, and if we assume that the other sources of funds will not respond in reaction to the government increase (the elasticities are not significant and so are equal to zero), the final value would be 0.65.

Table 5.2: Crowding in and Crowding out

	Ω	Ψ	Ψ1	Ω*Ψ	Ω*Ψ1
Government Funds	0.650	1.000	1.000	0.650	0.650
Business Funds	0.070	0.000	0.560	0.000	0.039
Other Funds	0.280	0.000	-1.450	0.000	-0.410
Total	0.650			0.650	0.279

6 The Productivity of UK Science.

The aim of this section is to develop a set of preliminary estimates of the science production function in the UK at the field level. To do so, a completely new dataset was designed and built by Evidence. Evidence created two unified data series linking the older Universities Statistical Record (USR) data with similar data from the databases of the Higher Education Statistics Agency (HESA) and the Research Assessment Exercise 1996 (RAE 1996). The USR data relates only to 'old' (pre-1992) universities, thus only data relating to these institutions from the HEFCE and RAE datasets were used. Standardising the datasets required a new common subject categorisation to be developed. This was a 30 subject aggregation of the RAE1996 UoAs and the HESA Cost Centres. The graduate research student data links Universities Statistical Record (USR) data with comparable data from the Research Assessment Exercise 1996 database (RAE 1996). These two datasets overlap in years 1992-93 and 1993-94. Since the totals for the two datasets were broadly similar, values in these two years are a mean of the values in each dataset (where both values are non-zero) and the non-zero value where one value is zero. The financial data link

USR data with similar data from the HESA database. These two datasets are contiguous - the USR data runs up to 1993/94; the HESA data begins in 1994/95. Early analyses confirmed that, despite marginal changes in data specification between the two, they were truly comparable and no adjustments to either sets were needed. In Appendix C we provide more detailed information about the methodology.

The SPRU SCIENCE dataset includes information about 52 'old' universities for 30 scientific fields during the 18 year period 1984/85 to 2001/02.[24] 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 total number of observations in this micro dataset is 28,080. This dataset has basically two variables (apart from the institution and field ids): information on Total Research Grant and Contract income and total number of graduate students.[25] Unfortunately, we do not at the moment (but it can be built in the future) have information for the other research outputs, i.e. publications and citations: the available information is still aggregated only at field level. Therefore, we had to build a new dataset in which information about research income and numbers of graduate students was aggregated to field level. The resulting dataset (SPRU SCIENCE FIELD) has a total of 540 observations.

Table 6.1 summarises the main research outputs used in this section. Across the entire period, there is a remarkable stability in the distribution of the research outputs by field. Broadly speaking, Natural and Medical Sciences respectively account for 75% and 85% of total publications and citations respectively in the UK. The remainder is split between Engineering (15% and 8% respectively) and Social Sciences (10% and 6% respectively). The context changes dramatically when we focus on graduate student research output. In this case, the importance of Natural Sciences declines to slightly over 30% at the end of the period, while the importance of Medical Sciences grows from 9% to 13%. Taken together, these two macro fields have a much lower output share (45% at the end of the period). The evolution of Engineering is stable at around 18% while Social Sciences shows a systematic growth from 28% to 36% towards the end of the period.

[24] The Open University, Cranfield University, and the independent University of Buckingham (not in USR statistics) and Lancaster (not in the HESA statistics) are not included in the list of the 52 'old' universities. Due to problems with the archiving of the USR data, London University data are the sum of all the colleges (see Appendix C1 for full list). Not all the universities are active in every scientific field every year.

[25] Total Research Grant and Contract income includes 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% of total research income in 2000/01 (http://www.ost.gov.uk/setstats/5/t5_1.htm; accessed on 17/5/2004). We were not able to obtain Total Research Income broken down by scientific fields because such a breakdown of HEFC funding by institution and subject area for the whole period was not available.

Table 6.1: 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.

On the basis of the SPRU SCIENCE FIELD dataset we:

- estimate the science production function for the OECD macro fields (natural sciences, engineering, medical sciences and social sciences) using information on 30 science fields available for the UK;
- estimate the aggregate science production functions for the UK in order to test if the disaggregate field model is a better specification than the aggregate, global, country level science production function and assess the existence and importance of spillovers across fields and institutions for Graduate Students;
- examine the changes in productivity growth across fields.

6.1 Field Level Estimates

In this section we present the results of the field level estimates of the science production function for publications, citations and graduate students.[26] Because information about research outputs is only available at field level, we cannot estimate knowledge production function for each of the 30 fields in the micro data. Instead, we need to aggregate the micro field into more broadly defined categories. This aggregation was done by mapping the 30 fields into the 4 broad categories of the

[26] Citation count has been corrected for the 'truncation problem' for most recent year as explained in Section 2.1.

OECD statistics. The matching is described in Table 6.2. The four macro fields analysed were: natural sciences, engineering, medical sciences and social sciences. For each of these macro fields, the aim was to estimate a science production function in the form:

$$y_{it}^{F} = a_{i}^{F} + b^{F} W(r)_{it}^{F} + g^{F} X_{it}^{F} + u_{it}^{F}, \quad i = 1,.....N; F = 1,..J \quad (29)$$

where y_{it} is the (log) output of the research 'intermediate' output (papers, citations and research students) by scientific micro field i (we have 30 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 grant and contracts income by scientific micro fields and X_{it} is a vector of the control variables described below.

Table 6.2: Matching between the Micro Field and OECD Macro Fields

Micro Field	OECD Macro Field
CLIN MED	MEDICAL SCIENCES
CLIN DENT	MEDICAL SCIENCES
PHARMACY	MEDICAL SCIENCES
PRE-CLINICAL	MEDICAL SCIENCES
NURSING	MEDICAL SCIENCES
HEALTH	MEDICAL SCIENCES
GEOGRAPHY	NATURAL SCIENCES
PHARMACOL	NATURAL SCIENCES
VET	NATURAL SCIENCES
BIOL SCI	NATURAL SCIENCES
AG&FOREST	NATURAL SCIENCES
CHEMISTRY	NATURAL SCIENCES
PHYSICS	NATURAL SCIENCES
OTHER PHYS SCI	NATURAL SCIENCES
MATHEMATICS	NATURAL SCIENCES
IT & IS	ENGINEERING AND TECHNOLOGY
GEN ENG	ENGINEERING AND TECHNOLOGY
CHEM ENG	ENGINEERING AND TECHNOLOGY
CIVIL ENG	ENGINEERING AND TECHNOLOGY
ELEC ENG	ENGINEERING AND TECHNOLOGY
MECH ENG	ENGINEERING AND TECHNOLOGY
MINING & MATERIALS	ENGINEERING AND TECHNOLOGY
ARCHITECT & PLAN	ENGINEERING AND TECHNOLOGY
PSYCHOL	SOCIAL SCIENCES
SOCIAL & LAW	SOCIAL SCIENCES
BUS & MANAGE	SOCIAL SCIENCES
LANGUAGES	SOCIAL SCIENCES
HUMANITIES	SOCIAL SCIENCES
ARTS	SOCIAL SCIENCES
EDUCATION	SOCIAL SCIENCES

Source: Evidence

In order to estimate equation (29) we need to specify both the time lag to be considered and the shape of the lag pattern function (W). and To do this we applied the methodology described in section 2.4 above. As before, a 6 year lag for publications and graduate students and a 7 year lag for citations were considered;[27]

[27] Although in this case the sequence of tests used to detect the optimum lag structure were not so robust as in the previous sections, considering 6 to 7 lags still seems a rather conservative approach

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. In all cases we also tested an unconstrained model and we 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 the time constraint for many (but not all) university researchers is how it is allocated between research and (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.[28]
- *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, of smaller size 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 18th century.
- *19th Century Universities*: is the proportion of research income in each field allocated to universities founded in the 19th century.
- *20th Century Universities*: is the proportion of research income in each field allocated to universities founded in the first half of the last century.

based on the known statistical result that omitting a 'relevant' lag has a much more serious consequence than including an irrelevant one (see Green, 1993).

[28] This variable was built using the HESA dataset only. We first computed the total number of students by university and field. From this total we subtracted the total number graduate students obtained from the dataset prepared by Evidence (which is based on more disaggregated data). For each university and field we also computed the total number of staff (which includes both research and teaching staff). And, finally, we computed the ratio between them (undergraduate students divided by staff). We have also re-computed this ratio at field level by aggregating the numbers within each university. The information for the 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 that using university level linear interpolation, which respects the heterogeneity across universities and fields.

- *Post WWII universities*: is the proportion of research income in each field spent in universities founded after the Second World War, mostly redbrick universities.

One limitation to the data provided for this investigation is that we did not have access to individual information about the colleges that form the 'collective' University of London. The reason for this is that the USR data held at the UK data archive (the only remaining electronically held form of USR data) record only a single figure for the University of London. This aggregation is problematic because the University of London comprises independent institutions (the colleges) with independent funding and decision making power. For example, the colleges decisions varied regarding membership of the Russell Group or 1994 Group associations. Additionally, the colleges were founded at different dates, making the allocation of an 'age' to the University of London rather problematic. All of this means that, unless we can reclassify the University of London, our definitions about Russell or 1994 Group and the age strata will be measured with error, and their impact underestimated. Thus, an analysis of research outputs at the university level would be more robust.

The coefficients of these control variables capture, to some extent, 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 put forward. 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 give more importance to research and, therefore, more support; this should translate into a higher research productivity.

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

6.1.1 Publications

We first show the pattern of weights and then proceed with the results of the model. As is clear from Figure 6.1, a first important result of our estimation is that the lag structures are significantly different across fields. Social Sciences have a relatively important impact in the short run (during the first two years) but the effects diminish over time; the situation in Natural and Medical Sciences, where the bulk of the impact is concentrated towards the end of the lag span, is completely the opposite. Finally, in the case of Engineering we have a clear parabolic function that 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 shows a much more immediate reaction 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, when we see a greater impact from Natural and Medical Sciences.

Figure 6.1 Restricted Pattern of Weights (Publications), by fields

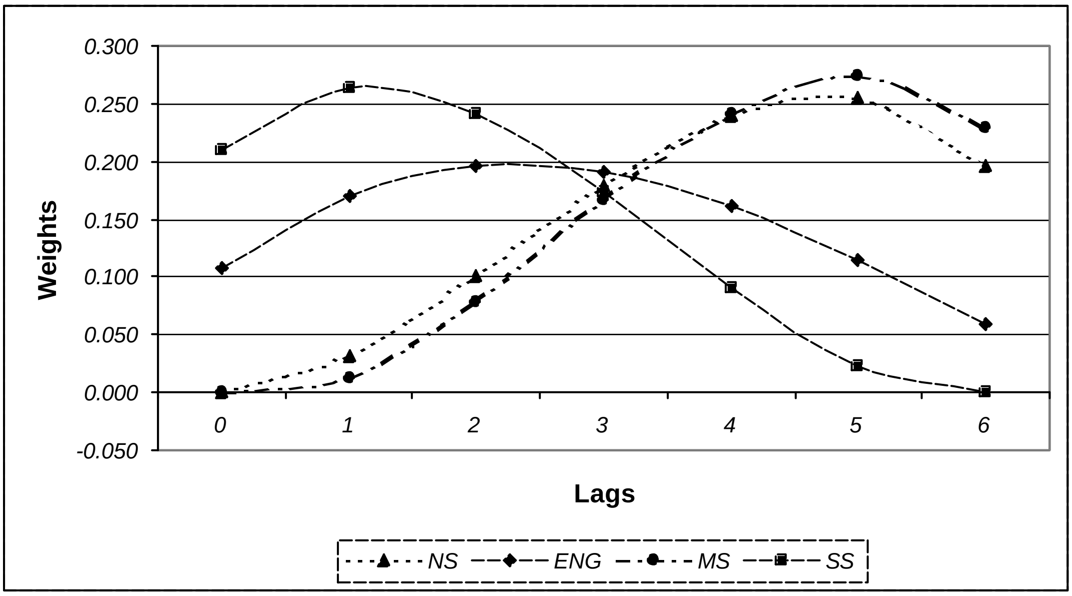

Table 6.3 presents the results of using the described weighting pattern to compute the sector knowledge stock and to estimate model (29). The first interesting result is that the long run elasticity between knowledge stock and research output publications varies widely across broadly defined fields. 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. As pointed out in Section 2.5, 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 the international spillover effects. The year trend value is highest for Engineering Sciences, smallest for Medical Sciences.

In terms of the impact distribution of changes in research budget, the last two rows of Table 6.3 show the median lag (the year that accumulated at least 50% of the impact) and the 90th 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 90% of the effect is reached only after five and half years.

Table 6.3: UK Levels Estimates, Publications
(Method: field fixed effect)

	Natural Sciences	Engineering	Medical Sciences	Social Sciences
HERD	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%

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 load 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, it is rather surprising to find that a higher allocation of funds to London based universities results in a slightly less productive system in Social Sciences. Third, 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 Engineering and Medical Sciences; no significant effect can be identified for the Russell Group universities.[29] Fourth, a larger share of funds to the Medieval universities was shown to result in a more productive system in Social Sciences but would have a negative impact in Medical Sciences. A larger share of funds to the 19th Century universities had a positive effect on the research output in Engineering and Social Sciences and a negative impact in Medical Sciences. The comparator groups for the university history is the group of universities founded after WWII. Finally, the tests for validity of the constraints were never rejected.

6.1.2 Citations

Citation output was analysed following the procedure used for publications. Figure 6.2 shows the pattern of weights on the different disciplines. The citations results appears similar to publications. Again, the citation output in Social Sciences tends to respond more quickly than other scientific fields to an increase in HERD investment. Medical Sciences does not show its largest research impact until the end of the time period, while for Natural Sciences and Engineering the polarisation is less strong. The difference from the publication lag structure that is worth mentioning is the very similar pattern for Engineering and Natural Sciences: Engineering has a less symmetric profile and behaves much more like Natural Sciences.

Figure 6.2 Restricted Pattern of Weights (Citations), by fields

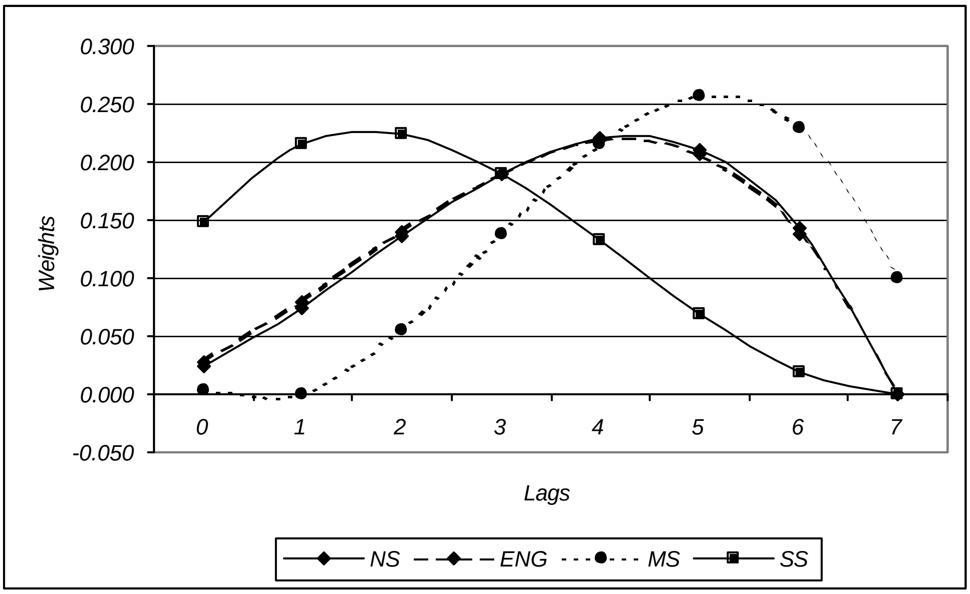

Table 6.4 presents the results of the estimation of model (29) in the case of citations output. In terms of the long run science budget elasticity the results are very similar to the results for publications. The highest elasticity is found in Medical Sciences (0.61), while the lowest is for Engineering Sciences (0.15), which was non-significant. The time trend variable was always positive and significant in three of the considered fields 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

[29] The higher output can be due to two phenomena: higher productivity of the 1994 Group universities or the competition effect from the other universities that received less funds. Only with micro data at the level of the university could these two effects be disentangled. This reasoning applies to the other resource allocation control variables.

after about 4 years, while the longest impact is in Medical Sciences where 90% of the effect is reached after 6 years.

Table 6.4: UK Levels Estimates, Citations (Method: field fixed effect)

	Natural Sciences	Engineering	Medical Sciences	Social Sciences
HERD	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***
19th Century	0.001	0.006	-0.008	0.009
	0.004	0.003**	0.004*	0.004**
20th 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. In contrast to the case of publications, 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 productivity in Medical Sciences, but a negative impact in Engineering Sciences. The teaching variable is again negative, with it's 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 19th Century universities with the adjunct of a positive impact for

Engineering. Finally, as before, the constraints implied by the model were not rejected.

6.1.3 Graduate Students

The third and final science output we examined at the field level for the UK is the 'production' of graduate students. Figure 6.3 shows the lag structure. The most interesting result of this analysis is that the patterns look very different to the ones estimated in the case of publications and citations. This result might come about because graduate students are a research output of a completely different nature to publications and citations. For instance, while Medical Sciences, Engineering and Natural Sciences show the strongest impact quite quickly (in the first three years), the impact in Social Sciences does not become evident until towards the end of the time frame. We do not have a definitive explanation about why this is the case, 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 sort of differential impacts.

Figure 6.3 Restricted Pattern of Weights (Graduate Students), by fields

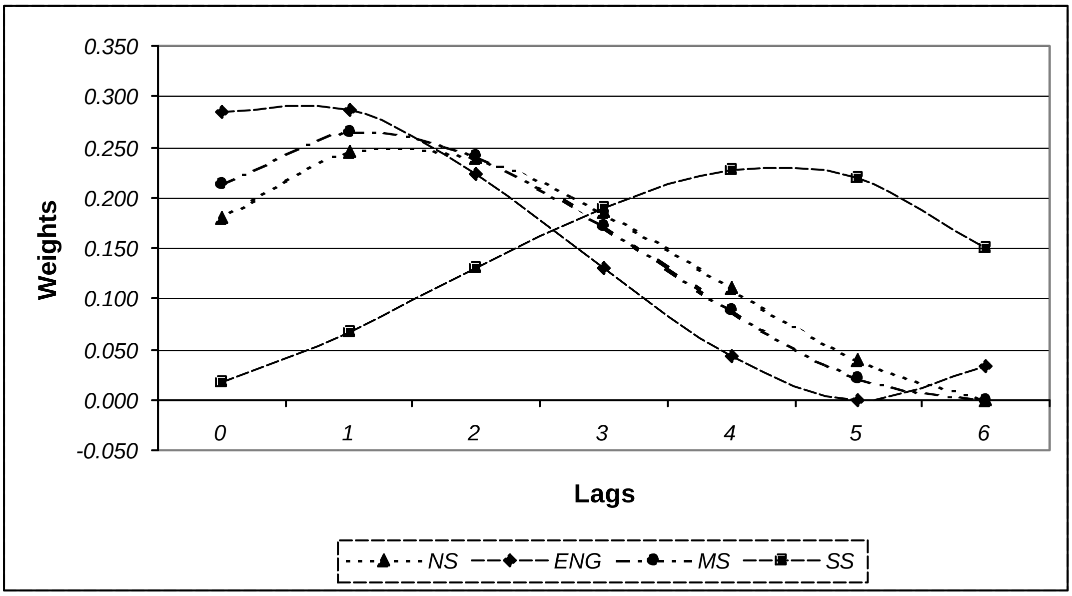

Table 6.5 shows the results of estimating model (29) using fixed effects. The largest elasticities regarding this type of research outputs can be found in both Natural and Medical Sciences with values of 0.54 and 0.65 respectively. The corresponding elasticities for the remaining two disciplines, Social 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 the 90% of the effect is felt only after 5 years.

Table 6.5: UK Levels Estimates, Graduate Students
(Method: field fixed effect)

	Natural Sciences	Engineering	Medical Sciences	Social Sciences
HERD	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*
19th Century	-0.014	-0.005	0.017	0.003
	0.007**	0.004	0.008**	0.004
20th 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%

Regarding the remaining control variables there were some interesting results. First, the undergraduate teaching variable is negative in Natural and Medical Sciences and Engineering, pointing to the fact that in these fields an increase in the undergraduate teaching load would negatively affect 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, we do not find any 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 in Social and Medical Sciences, while more funding to the 19th Century universities induces an increase in the university system output in Medical Sciences, but and a decrease in Natural Sciences. This last result also applied to the 20th Century universities, which in addition showed a positive premium in Social Sciences. The comparator group used as in the previous two estimations was the category of the Post WWII universities. Finally, as before, the constraints where not rejected in all the models.

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, as such, they must be considered as preliminary and exploratory results to be confirmed by other 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 to 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 other measures 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 for publications and citations the investment in R&D in Social Sciences affects these outputs more immediately than in the other three fields, in the case of gradate students most of the returns to the 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 can 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. Only with micro data at the level of the university would it be possible to identify which of the two effects is dominant.

How do our results compare with those reported in Adams and Griliches (1996) for the US? Broadly speaking these authors report two different sets of results. First, they work at aggregate level across 8 fields.[30] Second, they work within fields using university level information. Unfortunately, it is quite difficult to compare their results with ours for several reasons. First, the aggregate level analysis uses a different (and larger) number of fields than we used. In particular, Adams and Griliches do not consider Social Sciences and Natural Sciences is split over 5 different sub-fields. Moreover, their aggregate level analysis consists only of correlating the (lagged) R&D with the (log) publications and citations, without controlling for common trends between these two variables and then overestimating the true strength of the association between the science budget and research outputs. Finally, there are comparability problems with the work at field level. Adams and Griliches use regression techniques within the 8 fields they consider using a panel of those scientifically active universities within the fields and across time. However, their results do not control for university specific effects, over estimating the correlation

[30] Their fields were Agriculture, Biology, Chemistry, Computer Science, Engineering, Mathematics, Medicine and Physics.

between R&D investments and research outputs.[31] Keeping in mind these limitations, a quick comparison of the results points to not too dissimilar returns to scale, and both studies find higher elasticities for citations than for publications. Adams and Griliches (1996) explain the higher elasticity for citations by pointing out that while papers tend to 'leak' out of larger research programmes as doctoral students move to faculty posts in other smaller programmes, citations avoid this problem to an extent because research papers of young faculty cite papers from leading programmes where the doctoral research was carried out. We think that this explanation is also applicable to the UK given the high level of post-doctoral mobility.

6.2 Aggregate Estimates

In this section we pool all the fields and restrict them to the same elasticities. This enables us to answer two additional research questions. First, we have already identified field specific science production functions. But are these production functions systematically different across the macro fields? Or is it valid to assume the existence of a common country level knowledge production function as in the previous sections? Second, Griliches (1998) suggests that when working with more aggregated data (for instance, at industry level) the values of the elasticities relating to R&D impact on profits or productivity in the private sector are much higher than when working with data at firm or company level. Although this could be the result of measurement errors, which would have a greater effect at the micro level, it might also result from within sector spillovers being captured at industry level. When working at firm level (i.e. when measuring only the private returns to R&D) the estimate of the elasticities does not included the among firms spillovers. Based on Griliches's approach, we looked for the existence of spillovers (within institution and within field) for Graduate Students for which institution level data are available. *Within institution* Graduate Students spillovers refers to the positive effect exercised on the Graduate Students output by the existence of R&D investment in other scientific fields in the same university –e.g. mechanical engineering graduate students benefit from the existence of research in electronic engineering in the same university. *Within field* Graduate Students spillovers is represented by the fact that the R&D spending in a university in a given field has a positive impact on the number of Graduate Students produced by the other universities in the system -e.g. R&D grants received by the LSE business and management micro-field allow the development of research seminar series that are attended by graduate students of a large number of universities.

6.2.1 Aggregate versus disaggregate model: Which is the better specification?

In order to establish which is the best level of aggregation we have to compare the results for the field estimates with the results for the aggregate (common science production function) model. Table 6.6 provides the results of estimates with common elasticity for the variables used in the field estimates.

[31] It is interesting that in a note they present the results of the estimations controlling for university specific effects. In this case, all the correlations between R&D investment and research outputs become non-significant.

Table 6.6: UK Levels Estimates, Common Elasticity Models (Method: field fixed effect)

	Publications	Citations	Graduate Students
Herd	0.232	0.399	0.386
	0.078***	0.137***	0.166**
Year	0.029	0.014	0.018
	0.005***	0.007*	0.008**
London	0.003	0.002	-0.003
	0.001	0.004	0.004
Group94	-0.002	0.000	-0.001
	0.002	0.004	0.004
Russell	0.002	-0.002	0.001
	0.002	0.003	0.005
Medieval	0.003	0.000	0.000
	0.003	0.006	0.006
19^{th} Century	0.002	0.001	0.002
	0.002	0.004	0.004
20^{th} Century	0.002	-0.001	-0.001
	0.003	0.005	0.007
Teaching	-0.032	-0.036	-0.046
	0.007***	0.010***	0.012***
Constant	-52.878	-25.268	-33.383
	9.144***	12.370**	12.656***
Observations	348	342	348
R-squared	0.68	0.68	0.60

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

In order to establish if there are systematic differences across macro fields, we ran several Analysis of Variance (ANOVA) tests on the different research outputs. In each exercise we pooled the fields and added a fixed effect. After this we interacted the slopes of the model with the macro field effects and tested for statistical significance. A statistically significant result should be interpreted as evidence of changes in the slopes of the pooled model when we move across macro fields. The results of this exercise are summarised in Table 6.7 As can be seen from the data in the columns relating to significance of the interaction effects, the hypothesis about parameter constancy can be rejected for all research outputs and most of the variables (including that for size of the science budget). This points to the existence of field specific science production functions (even at the very aggregated level considered here) and the need to work with micro data in attempting to identify the underlying knowledge production function of the different fields. The assumption of a global country level science production function is very questionable.

Table 6.7: UK Levels Estimates, Testing the Common Elasticity Model (Method: Analysis of Variance)

	PUBLICATIONS					CITATIONS					GRAUDATE STUDENTS				
Observations	348		R-squared	0.996		341		R-squared	0.996		318		R-squared	0.991	
Root MSE	0.092		Adj R-squarec	0.994		0.122		Adj R-squarec	0.994		0.104		Adj R-squarec	0.989	
Source	Partial SS	df	MS	F	Prob>F	Partial SS	df	MS	F	Prob>F	Partial SS	df	MS	F	Prob>F
Model	505.159	64	7.893	969.650	***	1137.74	64	17.777	1187.89	***	1137.742	64	17.777	1187.89	0.000
fixed effect	38.587	28	1.378	169.300	***	112.85	28	4.030	269.300	***	17.210	28	0.615	56.12	***
year*fields	0.543	4	0.136	16.680	***	0.199	4	0.050	3.320	**	1.200	4	0.300	27.4	***
herd*fields	0.360	4	0.090	11.050	***	0.837	4	0.209	13.980	***	0.698	4	0.175	15.94	***
london*fields	0.014	4	0.003	0.420		0.050	4	0.012	0.830		0.174	4	0.043	3.96	***
group94*fields	0.059	4	0.015	1.820		0.077	4	0.019	1.280		0.161	4	0.040	3.66	***
russell*fields	0.086	4	0.022	2.650	**	0.155	4	0.039	2.600	**	0.243	4	0.061	5.54	***
medieval*fields	0.313	4	0.078	9.610	***	0.509	4	0.127	8.500	***	0.262	4	0.066	5.99	***
19th century*fields	0.134	4	0.034	4.130	***	0.111	4	0.028	1.850		0.209	4	0.052	4.76	***
20th century*fields	0.092	4	0.023	2.820	**	0.048	4	0.012	0.810		0.195	4	0.049	4.44	***
teaching*fields	0.843	4	0.211	25.890	***	1.248	4	0.312	20.850	***	0.279	4	0.070	6.36	***
Residual	2.304	283	0.008			4.145	277	0.015			2.782	254	0.011		
Total	507.463	347	1.462			1141.887	341	3.349			340.745	318	1.072		

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

6.2.2 The spillover analysis

In this section we look for the existence of spillovers across fields and institutions. A rough estimate of the magnitude or just the presence of spillovers can be obtained by comparing how the science budget elasticity changes when we move across different levels of aggregation. Strictly speaking, if there are spillover effects, we should see that the value of this key parameter moves up with the level of aggregation (that is, once the spillovers are internalised). We focus on Graduate Students because this is the only output for which we have micro data at the level of university department.

In the previous section we put forward some evidence that the science production functions are different across even broadly defined macro-fields; thus, in this analysis, we provide estimations for each of the macro-fields. We adopt a bottom up approach. First, we estimate the Research Grant and Contract income elasticity working at department (the 30 micro-field), university and year level. Second, we estimate the Research Grant and Contract income elasticity with the micro-fields aggregated in the 4 macro fields, but *within university.* For each macro-filed we run a regression with active universities in that macro-field and year. This allows us to capture the between micro-fields within university spillovers. Thirdly, we aggregate the research budgets for all the universities within the micro-fields in order to compute the *within field* (among universities) impact. For each macro-filed we run a regression with micro-fields forming the macro-field and year This allows us to capture the between universities within micro-field spillovers.

Table 6.8: UK Levels Estimates, at different levels of aggregation: The case of graduate Students

level	Fully Disaggregated				Within University				Within Field			
	NS	ENG	MS	SS	NS	ENG	MS	SS	NS	ENG	MS	SS
HERD	0.250	0.274	0.375	0.009	0.437	0.518	0.353	0.151	0.613	0.397	0.677	0.249
	0.020***	0.027***	0.042***	0.019	0.044***	0.052***	0.089***	0.046***	0.164***	0.112***	0.135***	0.095**
Year	0.003	0.021	0.063	0.080	-0.025	0.003	0.071	0.071	-0.020	0.016	0.051	0.066
	0.002	0.003***	0.006***	0.003***	0.004***	0.003	0.010***	0.004***	0.010*	0.006***	0.011***	0.007***
Constant	-5.975	-42.002	-128.713	-155.896	48.108	-9.052	-142.690	-137.940	36.576	-31.636	-107.524	-127.665
	4.262	5.826***	11.141***	5.457***	6.845***	6.246	19.718***	6.887***	18.076**	10.637***	20.313***	12.610***
Obs	2535	1800	736	2502	512	517	350	539	99	88	66	77
N. of id	262	215	89	263	47	47	36	49	9	8	6	7
R2	0.10	0.13	0.40	0.31	0.18	0.21	0.42	0.62	0.25	0.41	0.8	0.85

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

Columns 2 to 5 in Table 6.8 present the most possible disaggregated results, where the unit of analysis is the department (the micro-field) within the university. The highest elasticity here for Medical Sciences (0.37) while the lowest is for Social Sciences (0.01). The next four columns in the table present results with university as the unit of analysis. Here we aggregated all the micro-fields within the 4 macro-fields for each university. The aim was to capture the potential spillovers across the micro-fields but within universities. Here the highest elasticity is for Engineering (0.52) while the lowest is again Social Sciences (0.15). However, what is more significant is that in three of the broad macro-fields the elasticity is higher than for the Fully Disaggregated results as expected. The biggest Within University spillovers are in Engineering (0.24), followed by Natural Sciences (0.18) and Social Sciences (0.14). The only sector where we failed to find significant within university spillovers was Medical Sciences. The last 4 columns of the table refer to Within Field spillovers. Here, we aggregated the information from every university within the corresponding micro-field. The highest elasticity in this case was for Medical Sciences (0.67) with the lowest Social Sciences (0.25). If we compare these Within Field results with the Fully Disaggregated results, we find that the largest spillovers among universities are in Natural Sciences (0.36), while the lowest are in Engineering (0.12).

Broadly speaking we can say that the level of aggregation matters and that there is clear evidence of the presence of spillovers in the 'production' of graduate students. What differs across sectors is the effects of these spillovers. In three of the four-macro fields, spillovers are more important among different universities within the micro-fields rather than within a university across the macro-fields. The exception is Engineering where it appears that the spillovers between micro-fields within a university are much more stronger than spillovers between universities with a micro-field.

6.3 Productivity Analysis

This final section of the report focuses on the efficiency with which the domestic stock of knowledge (the 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? Following the methodology developed in section 3 we compute 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 (30) as:

$$tfp_{it}^{F} = y_{it}^{F} - b^{F} W(r)_{it}^{F}, \quad i = 1,.....N; F = 1,...J \quad (30)$$

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 (30) we first need an estimation of the elasticity coefficients by field (the βs) We used the field level results shown in Tables 6.3 to 6.5. Given the lags used in the construction of $W(r)_{it}$ we can only focus on productivity evolution during the 1990s.

Figures 6.4, 6.5 and 6.6 show the evolution of the TFP index by field over time for each of the research outputs. Two clear patterns emerge. In all the 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 output of scientific research, the productivity of UK science has increased along the 1990s. However, from the mid 1990s to, in all the macro fields, there has been a remarkable slowdown in productivity growth rates as highlighted by the less steep slopes of the productivity indices at the right of the figures. These observations are validated in Tables 6.9 to 6.11 where we show annual productivity growth rates.

Figure 6.4. TFP Publications

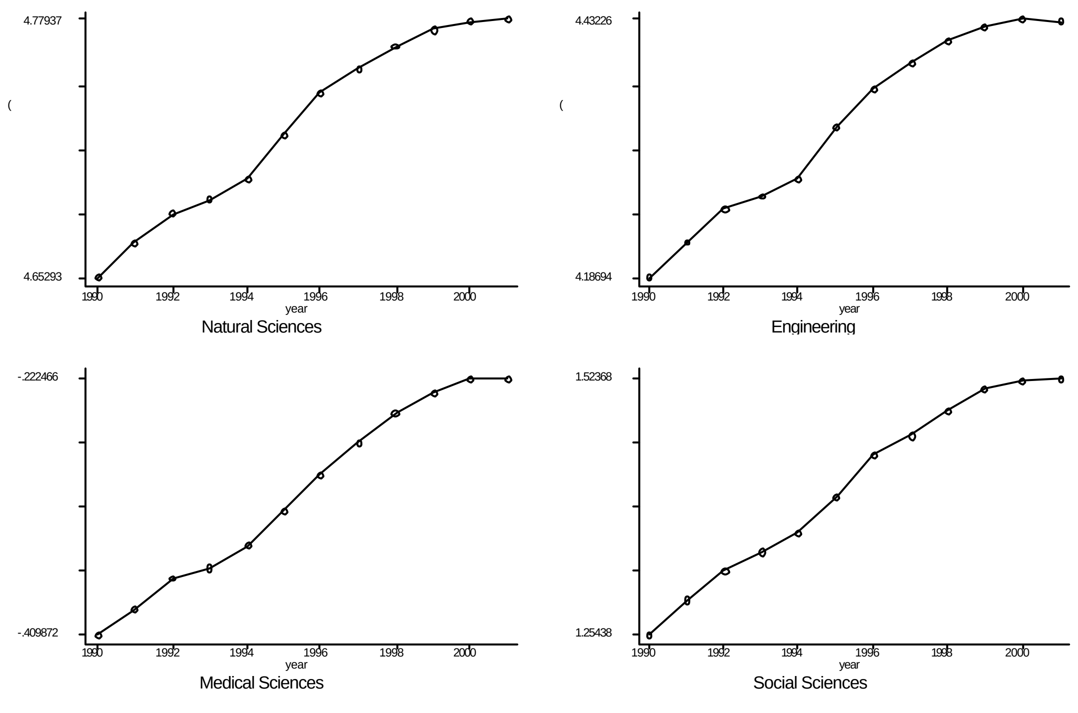

Figure 6.5. TFP Citations

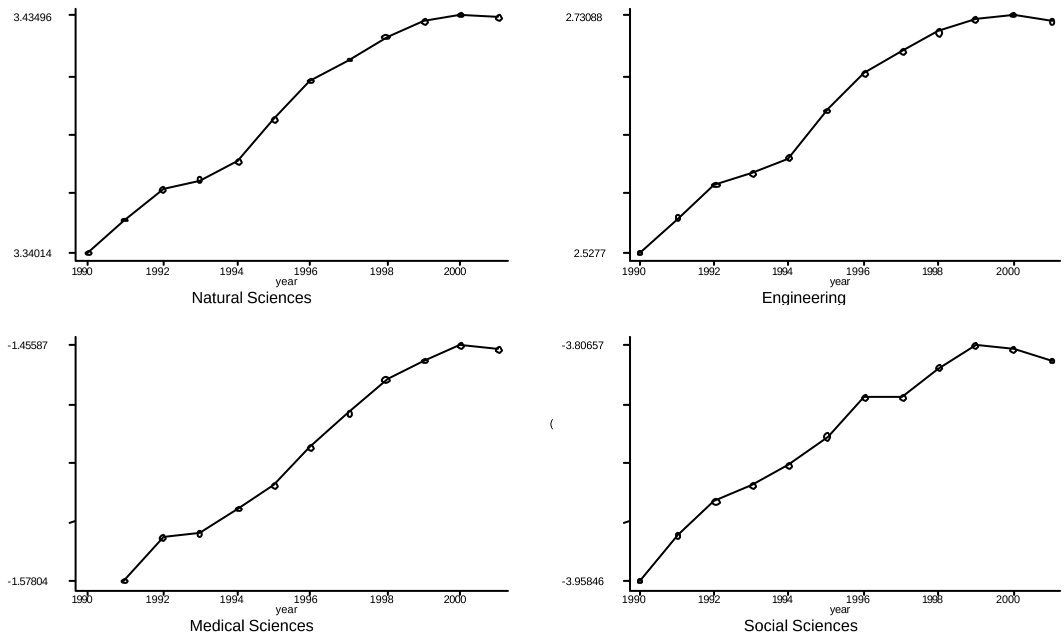

Figure 6.6. TFP Graduate Students

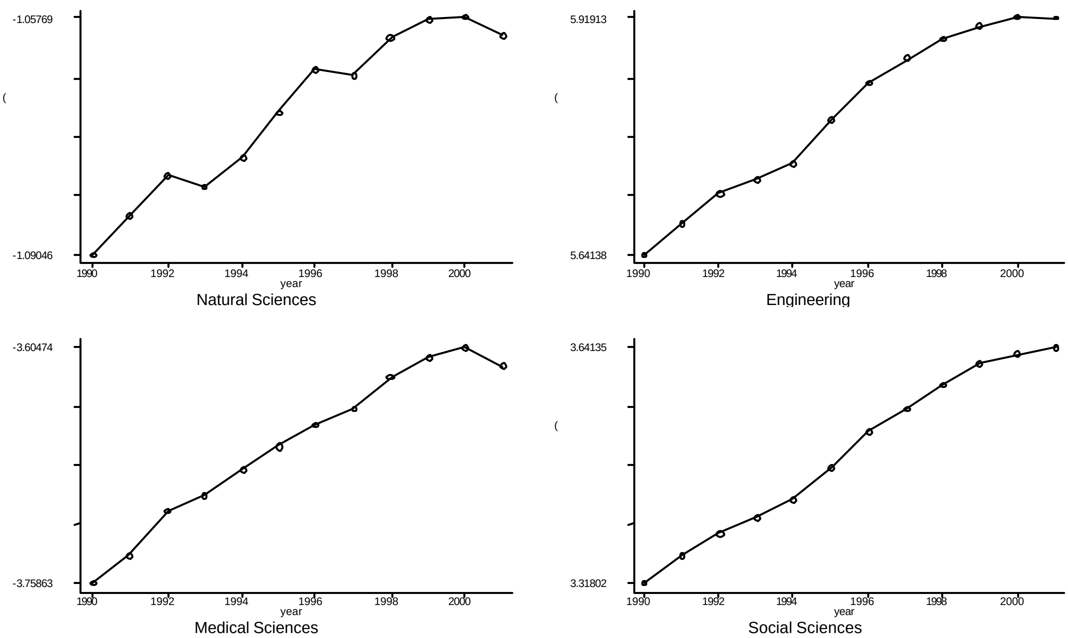

Table 6.9: UK Levels Estimates, TFP growth rates by Field: Publications

year	NS	ENG	MS	SS	NS	ENG	MS	SS
1991	1.6	3.3	1.8	3.7				
1992	1.5	3.2	2.4	3.0				
1993	0.6	1.3	0.7	2.0				
1994	1.0	1.7	1.6	2.1				
1995	2.2	4.8	2.5	3.8				
1996	2.0	3.7	2.7	4.4	1.5	3.0	2.0	3.2
1997	1.2	2.5	2.3	1.9				
1998	1.2	2.1	2.1	2.8				
1999	0.8	1.3	1.4	2.3				
2000	0.4	0.7	1.2	0.6				
2001	0.1	-0.3	0.0	0.4	0.7	1.3	1.4	1.6
Total	1.2	2.2	1.7	2.4				

Table 6.9 shows the results for publications. Across the whole period the TFP growth rate in the case of publications has fluctuated between 1.2% to 2.4% with the lowest value in Natural Sciences and the highest Social Sciences. The last four columns of Table 6.9 give average TFP growth rates during the first half of the 1990s compared to the same indicator for the 1990s to 2001. The cut-off point of 1996 was chosen to coincide with the 1996 RAE. The data show a remarkable slowdown in productivity. TFP productivity growth rates declined by more than 50% in Natural Sciences, Engineering (the largest decline) and Social Sciences, but by ‘only’ 22% in Medical Sciences

Table 6.10: UK Levels Estimates, TFP growth rates by Field: Citations

year	NS	ENG	MS	SS	NS	ENG	MS	SS
1992	1.5	3.5	1.9	2.9				
1993	0.7	1.5	-0.1	1.9				
1994	1.0	1.9	0.9	2.0				
1995	2.3	5.3	0.9	3.6				
1996	2.1	4.2	1.4	4.4	1.5	3.3	1.0	3.0
1997	1.3	2.9	1.2	1.9				
1998	1.2	2.3	1.5	2.8				
1999	0.8	1.5	0.7	2.3				
2000	0.4	0.8	0.5	0.7				
2001	0.1	-0.2	-0.5	0.4	0.8	1.5	0.7	1.6
Total	1.1	2.4	0.8	2.3				

Table 6.10 presents the same profile for citations. The highest growth rate is in Engineering Sciences (2.4%) while the lowest is 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.

Table 6.11 presents the results for graduate students. The results 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 '90s 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.

Table 6.11: UK Levels Estimates, TFP growth rates by Field: Graduate Students

year	NS	ENG	MS	SS	NS	ENG	MS	SS
1991	2.0	3.3	3.5	3.5				
1992	1.9	3.2	4.2	3.0				
1993	1.0	1.4	2.3	2.1				
1994	1.4	1.8	2.9	2.2				
1995	3.0	4.9	4.9	3.8				
1996	2.7	3.8	4.7	4.7	2.0	3.1	3.8	3.2
1997	1.8	2.5	4.3	2.6				
1998	1.5	2.2	3.4	3.1				
1999	1.1	1.4	2.5	2.7				
2000	0.7	0.8	1.9	1.1				
2001	0.4	-0.1	0.4	0.9	1.1	1.4	2.5	2.1
Total	1.6	2.3	3.2	2.7				

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 (see Tables D1-D3 in Appendix D). In our model the impact on research outputs of an increase of about 7% in 2000-01 is spread along 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) (see figures 6.1 and 6.2) and about 25% (again excepting Social Sciences for which it is near zero) in the case of Graduate Students (see Figure 6.3). 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 from the 1990s to 2001 due to the significant increase in the Science Budget 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.

The TFP estimations above have taken 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. Several different, and overlapping, explanations exist. One possibility is that in the period 1996-2001 the distribution of higher education funding lead to the system being less productive within each scientific field

(B and C estimations). Another possibility 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). In order 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 6.12 and 6.13.

Table 6.12: 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 the 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).

Table 6.13: 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 6.12 and 6.13. 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, that 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 when controlling for teaching intensity are similar. In this case, again, the results are relatively invariant. The exception is in Medical Sciences where, after controlling for teaching intensity, productivity growth rate reduces 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.[32] For the other research outputs the conclusions are similar to those for publications.[33]

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 staff conducting research. Underlying this hypothesis is that the lag in the relative compensations paid to researchers in the universities could have led to some 'high skilled' staff leaving academia (for positions overseas or for jobs in industry) and being replaced by an equivalent number of lower quality personnel. Third, due to the increase of other countries' publishing in English, UK researchers are facing increased competition to get their papers published in ISI journals, raising the bar to get published (a quality effect).[34]

All of these are 'pessimistic' explanations for the productivity growth slowdown. There is room for a fourth possibility, and one that is a bit more optimistic: the impact of the RAE. 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 that induced a productivity increase on the part of UK scientists. However, 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 level of the university and unit of assessment could help to clarify the current dynamics of the UK science system.

7 Conclusions

This report has analysed the determinants of the three most common university research outputs: publications (as a proxy for the production of codified research); citations (as an impact adjusted proxy for codified research production); and PhDs

[32] Student 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 the period 1991-95 declined every year from 8.4 in 1991 to 6.9 in 1995. This variable was more volatile in the second sub-period when it oscillated between 6.9 and 7.3.
[33] See Appendix F for TFP decomposition in the case of Citations and Graduate Students.
[34] Some evidence of this phenomenon has come to the fore in the US with a discussion on the US losing its dominance in the sciences to non-English speaking countries, being conducted on the front pages of the *New York Times* (see NYT, May 3, 2004).

awarded (as a proxy for the production of tacit knowledge accumulated in human capital). We estimated the two most commonly-used econometric specifications of knowledge production. Given that both specifications suffer from major limitations in the way that they treat the time lag between investment and return, we developed an alternative model to calculate the optimal time-lag structure. After specifying the most appropriate model, we focused on three specific issues: (1) assessment of knowledge spillovers among the 14 countries considered; (2) the time trends of productivity in different national scientific systems; and (3) analysis of the UK science system. The main results are summarised below.

(A) There is a strongly positive long-run impact (elasticity) between Higher Education R&D and all the research outputs examined. It is not possible to reject the hypothesis of constant returns to scale in the long run. There are important differences depending on the research output indicator considered. For publications and citations we found evidence of decreasing returns to the domestic component of R&D (with long run elasticity of 0.45 and 0.50 respectively for publications and citations), while there is some evidence of a much higher impact on human capital production (in terms of the number of PhDs awarded) in domestic HERD spending (with a long-run elasticity of 0.98).

(B) Analysis of international spillovers indicates that for publications and citations there is evidence of significant impact from the weighted investment in HERD in other countries (with long-run elasticity of about 0.50). When domestic elasticity is combined with international elasticity, we can identify slightly increasing returns at the international level (for all 14 countries considered).

(C) The above results refer to long-run impacts. However, there is also a long and quite complex lag structure with regard to the impact of domestic R&D on the different research outputs. These weights are quite different to those typically assumed in standard econometric models. There is no significant evidence of any positive impact in the first two years in the case of publications and the first three years in the case of citations. The total cumulative effects (the long-run elasticities) are spread over 6 and 7 years respectively, and reach a maximum towards years 5 and 6 respectively. Evaluation of the impact of science policies on the different research outputs must take account of this lag structure if erroneous conclusions are to be avoided.

(D) We attempted to develop a comparative analysis of the productivity of various different national science systems. We identify some important issues related to the dynamics of productivity. The US and UK science systems have the highest technological efficiency. However, the relative productivity of the US and UK systems has apparently been declining over the period considered. Because the decline in US relative productivity has been sharper, there is a form of 'productivity convergence' between the UK and the US. Most of the other countries considered (and particularly Germany and France) have experienced 'positive' productivity growth, meaning that they are catching up with both the UK and the US. These results may be influenced by the increased trend for non-English speaking countries to publish in English and, hence, to appear in the publications database constructed by ISI. However, there are two other possible policy explanations for these results that relate to the introduction of more competitive systems in the catching up countries and incentives for third-stream type activities in the two leading countries. These results call for cross-country analyses based on more detailed and more robust data.

(E) We investigated the relationships between different sources of finance for higher education research funding. We developed an approach to analyse the crowding in (or crowding out) phenomenon. Due to limitations in the data on sources of funds, the estimations are only preliminary; they should be considered merely as an indication of what could be done with more reliable data. Using some dynamic structural equations, we pointed to the presence of very complex feedback effects between three main sources: Government funds, Business contributions and Other (mainly from overseas and non-profit institutions). Government resources are the main source of funds, constituting two-thirds of the UK HE research budget. An increase in government resources is partially substituted for by Other funds and complemented by Business sources. In addition, Business sources and Other funds are also complementary. Once these effects are taken account of and 'reduced form' elasticities are considered, no statistically significant association between the different sources of funds is found. This suggests that the total impact of a given increase in government investment in HE research will be determined mainly by the importance of these other sources of funds in total research expenditure.

(F) The analysis of the UK science system (as represented by the old universities that account for about 90% of the R&D expenditures) 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-field. They are 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.

(G) 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, and Social Sciences seeing results in the first few years. This means, that the science system does not respond uniformly to changes in the sources of 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.

(H) In the case of Medical Science, 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.

(I) We included in the models a set of control variables. First, we controlled for the impact of different allocations of funding across types of institutions; the results are mixed and depend on the different research outputs. Some of these were significant pointing to the fact that different allocations of funds to universities result in higher or lower university system scientific production. Second, 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. Due to the limitations of the data at field level, the results on university specific factors, though interesting, should be considered as preliminary: they require validation through analysis based on micro data.

(J) Finally, we developed an analysis of the productivity of UK science and 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 '90s 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 journal 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 that pointed 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 part of the 1990s.

A final caveat is that the aim of this report was to test the feasibility of using econometric models to produce results that could contribute to the development of science policy. Given the shortcomings of most of the data used in this report (clearly highlighted in the main text) and the limitations imposed by the lack of micro data, the aim of this report was not to produce exact indicators of the dynamics of the science system and, on the basis of these, to draw strong policy conclusions. Rather, 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. They should be read as an example of how quantitative approaches combined with qualitative understanding of the system can contribute to the development of evidence based policy.

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Appendix A: The effects of using the wrong deflators

Let us assume the following static relationship between the knowledge stock and research output:

$$y_{it} = a + bc^{*}_{it} + n_{it} \quad (A.1)$$

where c(*) is the 'constant price' stock of knowledge deflated using the unknown HERD deflator. Using the fact that the variables are defined in logs, we can define this correctly deflated stock of knowledge as:

$$c^{*}_{it} = C_{it} - P_{it,Herd} \quad (A.2)$$

where upper case denote that the variable is in current prices. The problem is that we cannot observe (A.2) because we do not know the HERD deflator. Instead, we use the OECD GDP implicit deflator. This means we have a wrongly deflated stock of knowledge defined as follows:

$$c_{it} = C_{it} - P_{it,GDP} \quad (A.3)$$

In order to see the effects of working with (A.3) instead of (A.2), we can re-write (A.3) as:

$$\begin{aligned} c_{it} &= C_{it} - P_{it,GDP} + P_{it,Herd} - P_{it,Herd} \\ &= C_{it} - P_{it,Herd} + P_{it,Herd} - P_{it,GDP} \quad (A.4) \\ &= c^{*}_{it} + P_{it,Herd} - P_{it,GDP} \end{aligned}$$

Replacing (A.4) with (A.1) and re-arranging terms we obtain the following model:

$$y_{it} = a + bc_{it} + b\left(P_{it,GDP} - P_{it,Herd}\right) + n_{it} \quad (A.5)$$

Let us assume that, over time, the HERD deflator grows faster than the then implicit GDP deflator and that the relationship between both time trends can itself be approximated by a time trend:

$$\left(P_{it,GDP} - P_{it,Herd}\right) = p_0 - p_i T + e_{it} \quad (A.6)$$

By replacing (A.6) with (A.5), we arrive at a final empirical model that should include a time trend in order to control for the wrongly used deflators.

$$y_{it} = a' + bc_{it} - bp'T + n'_{it} \quad (A.7)$$

Appendix B: The Unit Root Tests

Following Maddala and Wu (1999) we estimated several variations of the following model:

$$\Delta y_{it} = r_i y_{it-1} + d\,t + \sum_{j=1}^{p_i} q_{ij} \Delta y_{it-j} + a_i + e_{it} \quad i = 1,.....N; t = 1,2,.....T \text{ (B.1)}$$

where Y_{it} is some variable of interest (publications, citations, HERD) and 't' is a deterministic trend. The Null Hypothesis (H0) is that the series has a stochastic trend (meaning ρ=1) and that they should be differenced before making any inference.[35] The alternative is that the series are either stationary or time-trend stationary. We have estimated the equation twice with and without the deterministic trend in order to give more power to some of the tests. We have used two different tests, the LL tests, (Levin and Lin, 1993) and the IPS test (Im, Pesaran and Shin, 1997). This second test is more flexible in terms of specification of the alternative hypotheses.

Table B.1 Testing for Unit Roots in the Panel (the LL test)

	coefficient	t-value	t-star	P-Value	Comments	
Publications	-0.3970	-7.7500	4.3560	0.0000	constant	trend
Citations	-0.0830	-3.9680	2.6240	0.0040	constant	
Publications	-0.5980	-9.9170	2.3810	0.0090	constant	trend
Citations	-0.0460	-2.1580	3.5890	0.0000	constant	
HERD	-0.4010	-10.5330	-2.5920	0.0050	constant	trend
HERD	-0.1250	-5.1860	-0.7580	0.2240	constant	

Tables B.1 and B.2 present the results of these tests. It is important to say that in all the series the time trend was always significantly different from zero; as a consequence we should only focus on the those tests where the time trend is included. The main conclusion is that we can reject the null hypothesis of a stochastic trend in all the series and in all the tests. As a robustness check, we also ran the tests without trends and, even in this more restrictive condition, in the majority of cases we reject the unit root hypothesis, except for two cases where each test led to contradictory results (we reject in one case but not in the other). Given these results we can consider the series as stationary, but with a deterministic trend. In what follows we work with these series in levels and we add a deterministic trend to the models.

[35] Unless one is only interested in some co-integration relationships.

Table B.2 Testing for Unit Roots in the Panel (the IPS test)

	t-bar	cv10	cv5	cv1	Psi[t-bar]	P-value	Comments	
Publications	-1.2690	-2.4500	-2.5300	-2.6900	2.7360	0.0030	constant	trend
Citations	-1.4560	-1.8200	-1.9000	-2.0700	-0.3490	0.3640	constant	
Publications	0.8620	-2.4500	-2.5300	-2.6900	11.8040	0.0000	constant	trend
Citations	1.4840	-1.8200	-1.9000	-2.0700	11.1860	0.0000	constant	
HERD	-2.6840	-2.4500	-2.5300	-2.6900	-2.1830	0.0150	constant	trend
HERD	-0.7630	-1.8200	-1.9000	-2.0700	3.0270	0.0010	constant	

Appendix C: Data Construction (prepared by Evidence)

Evidence Ltd
OST PSA target metrics for the UK Research Base
Data for economic analyses

Time-series data

The object of this piece of work was to produce two datasets linking data from the Universities Statistical Record (USR) to data from the Higher Education Statistics Agency (HESA) and from the Research Assessment Exercises (RAE) to produce continuous time series data from 1984/85 to 2001/02.

USR published data on the finances, students and staff at UK Higher Education institutions each year from 1984/85 to 1993/94. After this time this taks was taken over by HESA. Similar data were also collected by the Funding Councils as part of the RAE. Although the types of data collected are all alike, slightly different methodologies were used by each organisation and it is not an entirely straightforward matter to join the datasets.

The two datasets in question are:

Full time research graduate students at former-UGC funded institutions for the period 1984/85 to 2001/02 by institution and 30 custom subject fields

Research grant and contract income at former-UGC funded institutions for the period 1984/85 to 2001/02 by institution and 30 custom subject fields.

USR Data

USR data are stored in the UK Data Archive www.data-archive.ac.uk. The Finance dataset contains details of income and expenditure, and student load for all the Universities Funding Council (UFC) funded universities in Great Britain, with corresponding figures for Queens University, Belfast and the University of Ulster (Northern Ireland.[36] We used data on total research grant and contract income, and full-time research graduate students by institution, cost centre and year.

These data were supplied in a series of comma separated value files: 6 files per year for each year from 1984/85 to 1993/94. Within each spreadsheet, the data are held separately by subject, seven subject tables per spreadsheet.

For each dataset, category data in each year were compared with data in the following year to ensure that consistent use had been made of cost centres, institutions and data definitions. Then

- USR cost centres were mapped to SPRU group (see Annex C.1)

[36] USR were not responsible for supplying data from the Open University, Cranfield University, the independent University of Buckingham, or the former polytechnics and central institutions which were awarded university status from 1992 onwards.

- USR institutions were mapped to HESA institutions (see Annex C.2)[37]
- Year was mapped to a standardised year notation.

Research grant and contract income, and full-time research graduate data were then extracted from the USR data files and consolidated in separate files by USR cost centre, institution and year. These data were imported into a Microsoft Access database for analysis.

1986-87 data

On analysis it was discovered that values for both research students and research grant and contract income had been over-stated by a factor of two in the following cost centres.

Agric&Forestry
BioChemistry
Chemistry
Other Biol Sci
Other Med Stud
Psychology
Veterinary

This was corrected for, and the UK Data Archive notified.

These data were then mapped to SPRU group (see Annex C.1), SPRU institution (see Annex C.4) and standardised year, and aggregated by SPRU group.

HESA Data

HESA data (from 1994/95 to date) are available from HESA www.hesa.ac.uk either as off-the shelf products, such as 'HE Finance Plus', or as custom-specified datasets supplied on an ad hoc basis. Data are available in the following categories: students in HEIs, first destinations of graduates and leavers from HEIs, academic staff in HEIs, financial aspects of HEIs. We used total research grant and contract income data from 'HE Finance Plus' for the years 1995/96 to 2001/02, and a custom-specified dataset for 1994/95, in each case by institution, cost centre and year.

These data were supplied in a series of Microsoft Excel spreadsheets: two per year for each year from 1995/96 to 2001/02, and one for 1994/95.

For each dataset, category data in each year were compared with data in the following year to ensure that consistent use had been made of cost centres, institutions and data definitions. Then

- HESA cost centres were mapped to SPRU group (see Annex C.1)
- Year was mapped to a standardised year notation.

[37] No account has been taken of mergers.

Research grant and contract income data were then extracted from the HESA data files and consolidated in a file by HESA cost centre, institution and year. The data were imported into a Microsoft Access database for analysis.

Values were multiplied by 1,000 in order to revert from units of thousands of pounds to pounds.

These data were then mapped to SPRU group, SPRU institution and standardised year, and aggregated by SPRU group.

RAE Data

RAE data are available from www.hefce.ac.uk/research/assessment/ (1992 and 1996 exercises) and the Higher Education & Research Opportunities (HERO) website (2001 exercise) www.hero.ac.uk/rae/index.htm. Data are available in the following categories: academic staff, outputs (including publications), research students and research studentships, and external research income.

Total number of full-time research students on 31 December 1992, 31 December 1993 and thereafter 1 December of each subsequent year by institution and Unit of Assessment (from the RAE return).

These data are available as comma separated value files (with accompanying specification files), which were imported into a Microsoft Access database: one file for each exercise. Then

- RAE UoAs were mapped to SPRU group (see Annex C.1)
- Year was mapped to a standardised year notation.

Research grant and contract income data were extracted from the HESA data files and consolidated in a file by HESA cost centre, institution and year.

These data were then mapped to SPRU group, SPRU institution and standardised year, and aggregated by SPRU group.

Averages

There is overlap between the USR and RAE data in years 1992-93 and 1993-94. Values given here are a mean where both values are non-zero. Where one value is zero, the value given is the non-zero value.

Compiling the datasets

The USR and HESA research grant and contract income datasets were then appended, as were the USR and RAE research graduate datasets. Each was then queried and output as a flat file sorted in ascending order by InstName, Year, and SPRU GROUP.

The data were checked back to the original source files, and delivered by email to SPRU.

AppendixC.1

Institutions

USR published data from university institutions in Great Britain which formerly received Exchequer grants from the Universities Funding Council (UFC), together with corresponding figures for the Queens University, Belfast and the University of Ulster:

USR Name	HESA Inst Code	HESA name
Aston	0108	Aston University
Bath	0109	University of Bath
Birmingham	0110	University of Birmingham
Bradford	0111	University of Bradford
Bristol	0112	University of Bristol
Brunel	0113	Brunel University
Cambridge	0114	University of Cambridge
City	0115	City University
Durham	0116	University of Durham
E. Anglia	0117	University of East Anglia
Essex	0118	University of Essex
Exeter	0119	University of Exeter
Hull	0120	University of Hull
Keele	0121	University of Keele
Kent	0122	University of Kent at Canterbury
Lancaster	0123	University of Lancaster
Leeds	0124	University of Leeds
Leicester	0125	University of Leicester
Liverpool	0126	University of Liverpool
L. Bus. Sch	0135	London Business School
London	Mapped to sum of 'old' London institutions	
Loughboro'	0152	Loughborough University
M. Bus. Sch	0153	University of Manchester
Manchester	0153	University of Manchester
UMIST	0165	University of Manchester Institute of Science & Technology
Newcastle	0154	University of Newcastle-upon-Tyne
Nottingham	0155	University of Nottingham
Oxford	0156	University of Oxford
Reading	0157	University of Reading
Salford	0158	University of Salford
Sheffield	0159	University of Sheffield
Southampton	0160	University of Southampton
Surrey	0161	University of Surrey
Sussex	0162	University of Sussex
Warwick	0163	University of Warwick
York	0164	University of York
Aberystwyth	0177	University of Wales, Aberystwyth

Bangor	0178	University of Wales, Bangor
UWC Cardiff	0179	Cardiff University
Lampeter	0176	University of Wales, Lampeter
Swansea	0180	University of Wales, Swansea
U.W.Col.Med	0181	University of Wales College of Medicine
Aberdeen	0170	University of Aberdeen
Dundee	0172	University of Dundee
Edinburgh	0167	University of Edinburgh
Glasgow	0168	University of Glasgow
Heriot-Watt	0171	Heriot-Watt University
St. Andrews	0173	University of St Andrews
Stirling	0174	University of Stirling
Strathclyde	0169	University of Strathclyde
Belfast	0184	Queen's University of Belfast
Ulster	0185	University of Ulster

Prior to 1989 data were also published for 'Cardiff' and 'UWIST'. These institutions merged in 1989 to become USR's 'UWC Cardiff'. Lancaster is omitted, since it chose to withhold its data from HESA's 'HE Finance Plus' publication.

RAE and HESA data for 'London' institutions have had to be aggregated and summed to match the level at which USR publish their data: at institution level for the 'University of London'. These institutions are:

HESA name
Birkbeck College
Institute of Education
Goldsmiths College
Imperial College of Science, Technology and Medicine
Imperial College - National Heart and Lung Institute
King's College London
King's College - Institute of Psychiatry
Institute of Advanced Legal Studies
British Institute in Paris
Institute of Cancer Research
Institute of Classical Studies
Institute of Commonwealth Studies
Courtauld Institute of Art
Institute of Germanic Studies
Institute of Historical Research
Institute of Latin American Studies
University Marine Biological Station, Millport
Institute of United States Studies
School of Slavonic and Eastern European Studies
Warburg Institute
London School of Economics and Political Science
London School of Hygiene and Tropical Medicine
The London Institute

School of Oriental and African Studies
School of Pharmacy
Queen Mary and Westfield College
Royal Holloway, University of London
University College London
University College London - Institute of Child Health
University College London - Eastman Dental Institute
University College London - Institute of Neurology
University College London - Institute of Ophthalmology
Wye College, University of London

Appendix C.2

Subject areas

Differences in subject categorisation between organisations make it infeasible to use existing systems from either USR, HESA or the RAE. Evidence therefore created a new set of categories to standardise the subject-based data to a single series. The categories in this series are referred to here as the SPRU GROUP.

The USR cost centres are listed below.

USR Cost Centre Name	**SPRU GROUP**
Clin Medicine	CLIN MED
Clin Dentistry	CLIN DENT
Veterinary	VET
Pre-Clin Stud	PRE-CLINICAL
Anat/Physiolgy	PRE-CLINICAL
Nursing	NURSING
Other Med Stud	HEALTH
Psychology	PSYCHOL
Pharmacy	PHARMACY
Pharmacology	PHARMACOL
BioChemistry	BIOL SCI
Other Biol Sci	BIOL SCI
Agric&Forestry	AG&FOREST
Chemistry	CHEMISTRY
Physics	PHYSICS
Other Phys Sci	OTHER PHYS SCI
Mathematics	MATHEMATICS
Computing	IT & IS
General Eng	GEN ENG
Oth Technology	GEN ENG
Chemical En	CHEM ENG
Civil Eng	CIVIL ENG
Elec Eng	ELEC ENG
Mech,Aero,Prod	MECH ENG
Mineral Eng	MINING & MATERIALS
Metal,Material	MINING & MATERIALS
Architecture	ARCHITECT & PLAN
Planning	ARCHITECT & PLAN
Geography	GEOGRAPHY
Law	SOCIAL & LAW
Social Studies	SOCIAL & LAW
Business Mangt	BUS & MANAGE
Accountancy	BUS & MANAGE
Languages	LANGUAGES

USR Cost Centre Name	SPRU GROUP
Humanities	HUMANITIES
Creative Arts	ARTS
Education	EDUCATION
Adult Educatn	EDUCATION

Adult Education appeared for the first time in 1989.

Appendix C.3

The HESA cost centres are listed below.

HESA Cost Centre Name	**SPRU GROUP**
Clinical Medicine	CLIN MED
Clinical Dentistry	CLIN DENT
Veterinary Science	VET
Anatomy and Physiology	PRE-CLINICAL
Nursing and Paramedical Studies	NURSING
Health and Community Studies	HEALTH
Psychology and Behavioural Sciences	PSYCHOL
Pharmacy	PHARMACY
Pharmacology	PHARMACOL
Biosciences	BIOL SCI
Agriculture and Forestry	AG&FOREST
Chemistry	CHEMISTRY
Physics	PHYSICS
Earth, Marine and Environmental Sciences	OTHER PHYS SCI
General Sciences	OTHER PHYS SCI
Mathematics	MATHEMATICS
Information Technology and Systems Sciences	IT & IS
Computer Software Engineering	IT & IS
General Engineering	GEN ENG
Other Technologies	GEN ENG
Chemical Engineering	CHEM ENG
Civil Engineering	CIVIL ENG
Electrical, Electronic and Computer Engineering	ELEC ENG
Mechanical, Aero and Production Engineering	MECH ENG
Mineral, Metallurgy and Materials Engineering	MINING & MATERIALS
Architecture, Built Environment and Planning	ARCHITECT & PLAN
Geography	GEOGRAPHY
Social Studies	SOCIAL & LAW
Librarianship, Communication and Media Studies	SOCIAL & LAW
Catering and Hospitality Management	BUS & MANAGE
Business and Management Studies	BUS & MANAGE
Language Based Studies	LANGUAGES
French, Spanish & German Modern Languages	LANGUAGES
Other Modern Languages	LANGUAGES
Humanities	HUMANITIES
Archaeology	HUMANITIES
Design and Creative Arts	ARTS
Education	EDUCATION
Sports Science and Leisure Studies	EDUCATION
Continuing Education	EDUCATION

Appendix C.4

The RAE units of assessment are listed below.

RAE1996UoAName	**SPRU GROUP**
Clinical Laboratory Sciences	CLIN MED
Community Based Clinical Subjects	CLIN MED
Hospital Based Clinical Subjects	CLIN MED
Clinical Dentistry	CLIN DENT
Pre-Clinical Studies	PRE-CLINICAL
Anatomy	PRE-CLINICAL
Physiology	PRE-CLINICAL
Pharmacology	PHARMACOL
Pharmacy	PHARMACY
Nursing	NURSING
Other Studies and Professions Allied to Medicine	HEALTH
Biochemistry	BIOL SCI
Psychology	PSYCHOL
Biological Sciences	BIOL SCI
Agriculture	AG&FOREST
Food Science and Technology	CHEMISTRY
Veterinary Science	VET
Chemistry	CHEMISTRY
Physics	PHYSICS
Earth Sciences	OTHER PHYS SCI
Environmental Sciences	OTHER PHYS SCI
Pure Mathematics	MATHEMATICS
Applied Mathematics	MATHEMATICS
Statistics and Operational Research	MATHEMATICS
Computer Science	IT & IS
General Engineering	GEN ENG
Chemical Engineering	CHEM ENG
Civil Engineering	CIVIL ENG
Electrical and Electronic Engineering	ELEC ENG
Mechanical, Aeronautical and Manufacturing Engineering	MECH ENG
Mineral and Mining Engineering	MINING & MATERIALS
Metallurgy and Materials	MINING & MATERIALS
Built Environment	ARCHITECT & PLAN
Town and Country Planning	ARCHITECT & PLAN
Geography	GEOGRAPHY
Law	SOCIAL & LAW
Anthropology	SOCIAL & LAW
Economics and Econometrics	SOCIAL & LAW

RAE1996UoAName	SPRU GROUP
Politics and International Studies	SOCIAL & LAW
Social Policy and Administration	SOCIAL & LAW
Social Work	SOCIAL & LAW
Sociology	SOCIAL & LAW
Business and Management Studies	BUS & MANAGE
Accountancy	BUS & MANAGE
American Studies (Canada, the Caribbean, Latin America and the USA)	LANGUAGES
Middle Eastern and African Studies	LANGUAGES
Asian Studies	LANGUAGES
European Studies	LANGUAGES
Celtic Studies	LANGUAGES
English Language and Literature	LANGUAGES
French	LANGUAGES
German, Dutch and Scandinavian Languages	LANGUAGES
Italian	LANGUAGES
Russian, Slavonic and East European Languages	LANGUAGES
Iberian and Latin American Languages	LANGUAGES
Linguistics	LANGUAGES
Classics and Ancient History	HUMANITIES
Archaeology	HUMANITIES
History	HUMANITIES
History of Art, Architecture and Design	HUMANITIES
Library and Information Management	SOCIAL & LAW
Philosophy	HUMANITIES
Theology, Divinity and Religious Studies	HUMANITIES
Art and Design	ARTS
Communication, Cultural and Media Studies	ARTS
Drama, Dance and the Performing Arts	ARTS
Music	ARTS
Education	EDUCATION
Sports related subjects	EDUCATION

Appendix D: UK Science and Engineering R&D

Table D1: Total Government Science and Engineering Base R%D (constant prices, £ Million 2001-2002)

Net Government Expenditure on R&D by Departments													Estimated	Plan	Plan
In real terms	1990-91	1991-92	1992-93	1993-94	1994-95	1995-96	1996-97	1997-98	1998-99	1999-00	2000-01	2001-02	*2002-03*	***2003-04***	***2004-05***
OST			24.7	26.2	28.6	29.8	30.5	30.3	30.4	33.8	75.2	151.2	*278*	***350***	***498***
AFRC	101.7	98.7	120.9	133.6											
BBSRC					164.1	203.1	199	205.3	197.7	203.3	215.9	212.6	*233*	***245***	***248***
ESRC	45.6	42.6	53.6	60.3	66	65	65.6	65.2	68.3	69.2	65.9	68.1	*76*	***83***	***89***
MRC	254.6	262	284.5	311.5	321.8	322.9	315.8	310.3	296.1	318.4	322.4	346.5	*361*	***397***	***414***
NERC	180.6	154.3	154.7	164	168.2	182.7	167.7	168	171.8	167	173.7	166	*201*	***283***	***287***
SERC	576.9	566.9	625.4	692											
EPSRC					414.8	404.5	405.5	400.1	376.4	393.8	405.2	454	*462*	***419***	***426***
PPARC					217.1	237	239.5	216.1	220	194.3	210	214.3	*244*	***249***	***250***
CCLRC										2.1	2.1	10	*10*	***95***	***116***
Pensions/Other					35.4	9.2	10.7	15.6	13.6	21.2	25.1	25.8	*26*	***27***	***27***
TOTAL SCIENCE BUDGET R&D	1159.3	1124.5	1263.9	1387.6	1416	1454.2	1434.2	1410.8	1374.3	1403.1	1495.4	1648.6	*1891*	***2147***	***2355***
Higher Education Funding Councils															
UFC & PCFC	1184.6	1228.5													
HEFC			1206.9	1184	1227.2	1194	1168.4	1139.2	1165	1212.9	1307.9	1473.5	*1551*	***1583***	***1626***
TOTAL HE FUNDING COUNCILS	1184.6	1228.5	1206.9	1184	1227.2	1194	1168.4	1139.2	1165	1212.9	1307.9	1473.5	*1551*	***1583***	***1626***
TOTAL SCIENCE & ENGINEERING BASE R&D	2343.9	2353	2470.8	2571.6	2643.2	2648.2	2602.6	2550	2539.3	2616	2803.3	3122.1	*3442*	***3730***	***3981***
Base	1990-91	1991-92	1992-93	1993-94	1994-95	1995-96	1996-97	1997-98	1998-99	1999-00	2000-01	2001-02	*2002-03*	***2003-04***	***2004-05***
TOTAL SCIENCE BUDGET R&D	2.13%	-3.00%	12.40%	9.79%	2.05%	2.70%	-1.38%	-1.63%	-2.59%	2.10%	6.58%	10.24%	14.70%	13.54%	9.69%
TOTAL HE FUNDING COUNCILS	-3.50%	3.71%	-1.76%	-1.90%	3.65%	-2.71%	-2.14%	-2.50%	2.26%	4.11%	7.83%	12.66%	5.26%	2.06%	2.72%
TOTAL SCIENCE & ENGINEERING BASE R&D	-0.80%	0.39%	5.01%	4.08%	2.78%	0.19%	-1.72%	-2.02%	-0.42%	3.02%	7.16%	11.37%	10.25%	8.37%	6.73%

Source: ONS Government R&D Survey

Table D2: Research grant and contracts income in current prices (£ MM)

Year	NS	ENG	MS	SS	Total	NS %	ENG %	MS %	SS %	Total %
1984	114.09	67.78	110.63	39.07	331.56					
1985	134.49	79.43	127.68	45.19	386.79	17.9%	17.2%	15.4%	15.7%	16.7%
1986	156.01	94.63	151.06	54.02	455.72	16.0%	19.1%	18.3%	19.5%	17.8%
1987	173.50	97.15	172.28	60.80	503.73	11.2%	2.7%	14.0%	12.6%	10.5%
1988	213.57	106.70	207.95	71.75	599.97	23.1%	9.8%	20.7%	18.0%	19.1%
1989	256.47	128.67	245.17	86.27	716.58	20.1%	20.6%	17.9%	20.2%	19.4%
1990	296.19	143.72	294.46	102.62	836.99	15.5%	11.7%	20.1%	19.0%	16.8%
1991	308.23	149.22	329.85	107.92	895.22	4.1%	3.8%	12.0%	5.2%	7.0%
1992	378.19	181.59	380.81	115.80	1056.40	22.7%	21.7%	15.4%	7.3%	18.0%
1993	419.48	199.37	440.93	122.72	1182.50	10.9%	9.8%	15.8%	6.0%	11.9%
1994	463.57	218.22	423.15	135.13	1240.06	10.5%	9.5%	-4.0%	10.1%	4.9%
1995	497.16	223.17	439.79	146.58	1306.70	7.2%	2.3%	3.9%	8.5%	5.4%
1996	516.06	226.14	476.53	153.71	1372.44	3.8%	1.3%	8.4%	4.9%	5.0%
1997	556.09	233.79	530.49	157.53	1477.89	7.8%	3.4%	11.3%	2.5%	7.7%
1998	593.86	246.92	597.69	169.97	1608.45	6.8%	5.6%	12.7%	7.9%	8.8%
1999	642.75	248.27	645.04	191.78	1727.84	8.2%	0.5%	7.9%	12.8%	7.4%
2000	709.30	266.64	713.44	219.36	1908.73	10.4%	7.4%	10.6%	14.4%	10.5%
2001	783.06	295.15	778.89	250.43	2107.54	10.4%	10.7%	9.2%	14.2%	10.4%

Source Evidence; our elaboration

Table D3: Research grant and contracts income (constant prices, £MM 1995)

Year	NS	ENG	MS	SS	Total	NS %	ENG %	MS %	SS %	Total %
1984	190.28	113.04	184.51	65.16	552.97					
1985	212.26	125.36	201.52	71.32	610.46	11.6%	10.9%	9.2%	9.5%	10.4%
1986	238.26	144.52	230.70	82.50	695.97	12.2%	15.3%	14.5%	15.7%	14.0%
1987	251.63	140.90	249.86	88.18	730.57	5.6%	-2.5%	8.3%	6.9%	5.0%
1988	291.92	145.84	284.24	98.07	820.08	16.0%	3.5%	13.8%	11.2%	12.3%
1989	326.21	163.66	311.84	109.73	911.45	11.7%	12.2%	9.7%	11.9%	11.1%
1990	350.31	169.98	348.27	121.37	989.93	7.4%	3.9%	11.7%	10.6%	8.6%
1991	341.87	165.51	365.85	119.70	992.92	-2.4%	-2.6%	5.0%	-1.4%	0.3%
1992	403.40	193.70	406.20	123.52	1126.83	18.0%	17.0%	11.0%	3.2%	13.5%
1993	436.14	207.29	458.44	127.59	1229.47	8.1%	7.0%	12.9%	3.3%	9.1%
1994	475.55	223.86	434.09	138.62	1272.12	9.0%	8.0%	-5.3%	8.6%	3.5%
1995	497.16	223.17	439.79	146.58	1306.70	4.5%	-0.3%	1.3%	5.7%	2.7%
1996	499.72	218.98	461.44	148.84	1328.98	0.5%	-1.9%	4.9%	1.5%	1.7%
1997	523.43	220.06	499.33	148.28	1391.09	4.7%	0.5%	8.2%	-0.4%	4.7%
1998	542.98	225.77	546.48	155.41	1470.65	3.7%	2.6%	9.4%	4.8%	5.7%
1999	573.12	221.37	575.16	171.00	1540.65	5.5%	-1.9%	5.2%	10.0%	4.8%
2000	619.10	232.73	622.71	191.46	1665.99	8.0%	5.1%	8.3%	12.0%	8.1%
2001	664.23	250.36	660.69	212.43	1787.72	7.3%	7.6%	6.1%	10.9%	7.3%

Source: Evidence; our elaboration

Appendix E: TFP Growth Decompositions

Table E.1: TFP decompositions for Natural Sciences and Engineering, Citations

	Natural Sciences					Engineering				
Time	A	B	C	D	TOTAL	A	B	C	D	TOTAL
91-96	1.5	1.4	1.5	1.1	1.1	3.3	3.2	3.4	3.0	2.9
96-01	0.8	0.8	0.7	0.7	0.7	1.5	1.5	1.6	1.5	1.5
Total	1.1	1.1	1.1	0.9	0.9	2.4	2.4	2.6	2.3	2.3

Note: A controls only for the Science Budget, B is A plus controls for resources allocation by London, 1994 Group and Russell Group, C is A plus controls University Age, D is A plus controls for teaching intensity and Total is A plus (B+C+D)

Table E.2: TFP decompositions for Medical and Social Sciences, Citations

	Medical Sciences					Social Sciences				
Time	A	B	C	D	TOTAL	A	B	C	D	TOTAL
91-96	1.0	1.0	1.1	0.6	0.6	3.0	3.1	2.6	3.2	2.8
96-01	0.7	0.6	0.6	0.7	0.4	1.6	1.9	1.5	1.7	1.8
Total	0.8	0.8	0.9	0.6	0.5	2.3	2.5	2.1	2.5	2.3

Note: A controls only for the Science Budget; 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).

Table E.3: TFP decompositions for Natural Sciences and Engineering, Graduate Students

	Natural Sciences					Engineering				
Time	A	B	C	D	TOTAL	A	B	C	D	TOTAL
91-96	2.0	1.9	1.9	1.8	1.6	3.1	2.9	3.2	2.9	2.8
96-01	1.1	1.1	1.0	1.0	1.0	1.4	1.4	1.5	1.3	1.5
Total	1.6	1.6	1.5	1.4	1.3	2.3	2.2	2.4	2.2	2.2

Note: A controls only for the Science Budget; 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).

Table E.4: TFP decompositions for Medical and Social Sciences, Graduate Students

	Medical Sciences					Social Sciences				
Time	A	B	C	D	TOTAL	A	B	C	D	TOTAL
91-96	3.8	3.8	3.6	3.1	2.9	3.2	3.3	2.9	3.3	3.2
96-01	2.5	2.4	2.4	2.5	2.3	2.1	2.3	2.0	2.1	2.2
Total	3.2	3.2	3.0	2.8	2.6	2.7	2.9	2.5	2.7	2.7

Note: A controls only for the Science Budget. 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).