RAND EUROPE

The relationship between research spending and research performance

A cross-country and in-depth study

Joachim Krapels, Marco Hafner, Anne Kirtley, Enora Robin, Paulina Pankowska, Louise Lepetit, Jacopo Bellasio, Susan Guthrie

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Prepared for The Department for Business, Innovation and Skills

For more information on this publication, visit www.rand.org/t/RR1068

Published by the RAND Corporation, Santa Monica, Calif., and Cambridge, UK

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Summary

The United Kingdom has a world-class research system and, in comparison with similar industrialised countries, appears to be 'punching above its weight' in terms of research excellence. However, it could be at a comparative disadvantage in other areas of the research system, particularly in terms of investment.

This study investigates the relationship between spending and research performance through an econometric analysis that aims to understand the consequences of lower levels of investment in research. It also investigates potential nonlinearities in the relationship between spending and performance through a series of case studies.

The econometric analysis compares data on research spending with research performance as measured primarily through bibliometrics indicators, reflecting a focus on research performance rather than, for example, wider measures of innovation performance. The econometric analysis is conducted at two levels: a cross country analysis looking at the relationship between spending and performance and, in particular, the time-lags between them; and a more disaggregated analysis of funding patterns between different disciplines in the United Kingdom.

We find that there is a statistically significant relationship between changes in spending and changes in performance, when country factors are taken into account. This implies that changes in spending are correlated with changes in performance, meaning that a substantial increase or decrease in spending will have an effect on performance as measured in the number of publications produced. We also find that the average time-lag in this relationship is likely to be between two and four years. This means that it will take around two to four years for changes in research spending to be reflected in research performance as measured by bibliometric estimates of the quality and quantity of academic outputs. This trend is broadly reflected in the disaggregated analysis by discipline within the United Kingdom, although the limited dataset means that this analysis was less detailed than the cross-country analysis.

We also note that the United Kingdom remains one of the most productive countries in the production of Top 1% publications, and in comparison to a set of comparator countries, it is also most efficient in the production of the world's most cited publications. Per unit of higher education research funding, the United Kingdom produces the most publications in the top one per cent for their field internationally.

Through five case studies, we analysed 'nonlinearities in the relationship between funding and performance, focusing on two particular cases: 'cliff-edges', points where a small decrease in funding results in a significant decrease in some or all measures of performance; and 'take-off points', points where a small increase in funding improves performance significantly. We took a wider definition of research

performance here, looking at capacity as well as academic output. The case studies were based on interviews and document reviews and provide a detailed and nuanced description of the development of five research fields. Five general themes were identified across the five case studies. These provided more general substance to the notions of cliff-edge and take-off, and to the underlying relationship between research spending and research performance. The themes are:

1. **Cliff-edge and take-off depend on perspective**: In several cases it was found that what was perceived as a cliff-edge by some stakeholders, generally academia, was not perceived as such by other stakeholders, such as policy makers.
2. **The evolution of a research field can lead to different interpretations**: To some a field may evolve, to others it is in decline. Important in these judgements is how the field is defined: a broad conception of a field may yield a different judgment than a narrow conception. Looking at the drivers of change may provide insights into the background of the different judgments.
3. **It is crucial to understand the wider context around changes in performance**: In any study of change, context is important, and the case studies reconfirm the importance of understanding the context of wider policy issues, other changes in industry, economic factors, and the assessment of cliff-edges and take-offs. To view changes in research fields in isolation could yield inaccurate judgements about their development.
4. **The mechanisms through which spending decisions are translated into disproportionate changes in research capacity and excellence can vary**: We identify three key mechanisms through the case studies: changes in infrastructure; movement of researchers (geographically and between fields); and the organisations of research and researchers. Typically, these three interact in the translation of funding changes into performance changes.
5. **Early warning signs of disproportionate effects are not easy to identify**: We note that some signals currently used, such as individual reports and signals from areas outside of the research (e.g. in industry), should be treated with caution. Several of the cases of cliff-edge and take-off investigated were not as clear-cut as some of the statements serving as their rationale for inclusion implied. Policy motivations for funding and shifts in the demographics of the research community are potential markers for change based on the case studies, but require further investigation.

There is a clear link between the change in research spending and research performance, and our analysis suggests that the time-lags in this relationship are around 2-4 years. The time-lags work both in the case of investment and disinvestment. Work already 'in the pipeline' may still be finished despite declining budgets, which may give the appearance that a field stays healthy, yet decline will follow, albeit lagged. The way in which this relationship works, however, is complex and is likely to combine a range of factors including changes in infrastructure, movement of researchers, and changes in the structure and organisation of funding.

Specifically focusing on the United Kingdom, the country continues to perform well, not just in terms of overall performance, but also particularly in terms of efficiency in producing high quality research for a relatively lower level of investment than comparator countries. However, given these time-lags, continued lower levels of investment may take time to manifest in performance, and there may also be underlying differences between research fields. So how can the United Kingdom decide where to invest? Our analysis cautions against the use of simplistic 'warning signs' for the development of scientific fields. Looking at the humanities, there is evidence that simply using one bibliometric indicator for a field may not convey the entire picture, and may actually obscure wider development. In similar vein, warning signs analysed in the case studies, such as an individual expert's opinion, may not reflect the wider development of the field. This is reinforced by differences in perspective regarding the performance of fields and their evolution. More detailed analysis is required, drawing on a range of sources, to understand the performance and development of different research fields.

The study shows that the different types of evidence are useful and should be collected and analysed to better understand the research spending and performance. The data are strongest when used in combination, to complement each other, and thereby to produce a holistic view of the relationship between research spending and performance.

Acknowledgements

The authors would like to thank Alex Shirvani, Dominic Rice, and Dr Bryony Butland at the Department for Business, Innovation and Skills for their continued interest and support in the study.

We would also like to thank Dr Catriona Manville (RAND Europe) and Dr Sonia Sousa (previously RAND Europe, currently the National Audit Office) for their review of the document and constructive comments in their role providing Quality Assurance on this project. Furthermore, we would like to thank Professor Joanna Chataway, Professor Tom Ling and Dr Steven Wooding for their continuous support as Special Advisors to the project.

Finally, we would like to thank the expert panel for their interest throughout the project.

Abbreviations

AHRC	Arts and Humanities Research Council,
AIC	Akaike information criterion
BBSRC	Biotechnology and Biological Sciences Research Council
BERD	Expenditure on R&D in the Business Enterprise Sector
BIS	Department for Business, Innovation and Skills
DEL	Northern Ireland the Department for Employment and Learning
EPSRC	Engineering and Physical Sciences Research Council
ESRC	Economic and Social Research Council
GERD	Gross Domestic Expenditures on Research and Development
GDP	Gross Domestic Product
GovERD	Government Intramural Expenditure on Research and Development
HERD	Expenditure on Research and Development in the Higher Education Sector
HEFCE	Higher Education Funding Council for England
HEFCW	Higher Education Funding Council for Wales
MRC	Medical Research Council
NERC	Natural Environment Research Council
NHS	National Health Service
NMR	Nuclear Magnetic Resonance Spectroscopy
OECD	Organisation for Economic Co-operation and Development
PPARC	Particle Physics and Astronomy Research Council
R&D	Research and Development
SBIC	Schwartz/Bayesian information criterion
STFC	Science and Technology Facilities Council
SFC	Scottish Funding Council
STEM	Science, technology, engineering, and mathematics

1. Introduction

A recent international benchmarking of the UK science and innovation system[1] noted that the United Kingdom has a world-class research system that draws on the knowledge, skills, expertise and infrastructure of historically significant and modern institutions.[2] Comparisons with similar industrialised countries indicates that the United Kingdom is 'punching above its weight' in terms of research excellence, yet it is also observed, most recently in the Allas Report, that it may be at a comparative disadvantage in other areas of the research system.[3] The most problematic of these disadvantages, as identified by Allas, is the structural under-investment in research and innovation by the United Kingdom compared to similar countries. Compared to other advanced economies lower levels of investment are visible both in the public and private sector, and, if unaltered, could jeopardise the UK research base in the future.[4]

This report aims to further understand the 'relationship between research spending and research performance'.[5] Chapter 1 outlines the rationale for the study and considers in detail the two main research questions:

1. What is the relationship between spending and research performance?
2. What are the nonlinearities in this relationship?

The rest of the report is structured as follows. Chapter 2 outlines the research problem in detail and introduces the methodology used to address the two main research questions. Chapter 3 reports the findings of the econometric analysis to address the first research question. Chapter 4 reports on the key findings from the case studies related to the second research question. Chapter 5 presents the conclusions, and Chapter 6 contains detailed prospects for additional future research based on a review of currently available data and data that will potentially be available in the future.

[1] T. Allas, 'Insights from International Benchmarking of the UK Science and Innovation System' (London: Department for Business, Innovation and Skills, 2014).

[2] BIS (2014) The relationship between R&D spending and research performance, ITQ: RE140150BIS

[3] Allas, 'Insights from International Benchmarking of the UK Science and Innovation System'.

[4] Ibid.

[5] BIS (2014) The relationship between R&D spending and research performance, ITQ: RE140150BIS

1.1. Rationale for the study: The contribution of research

Research is a visible expression of human curiosity and illustrates a thirst for new knowledge. However, research and development (R&D) also performs an important social and economic function as through the creation of new knowledge, solutions can be found to problems. There is also evidence to suggest that investment in R&D has significant effects on productivity growth and economic welfare,[6] although the causal links are not always clear, and uncertainties remain.

Research into the economic benefits of research is varied,[7] however, at the aggregate country level it tends to consist of studies that investigate the impact of country level investments on a country's productivity and economic growth. In general, such studies show the positive impacts of public investments in R&D, however, Salter and Martin[8] note that the evidence of many studies is limited by methodological problems. Guellec and Van Pottelsberghe de la Potterie show that for 16 Organisation for Economic Co-operation and Development (OECD) countries, science and technology are important to productivity growth and economic growth, in particular public investments in the higher education sector.[9] Sena et al. also show that public investment in innovation can spur economic growth by the creation of an environment conducive to knowledge exchange.[10] Finally, Coccia notes that to maximise outputs there may be an optimal level of investment in R&D of 2.3 to 2.6 per cent of Gross Domestic Product (GDP).[11]

1.1.1. The importance of context

Broad and general evidence suggests that R&D can have a positive impact on GDP, but it is important to consider the country and institutional context when interpreting the above literature and the design of this study.

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[6] E.g.: D. Guellec and B. de la Potterie, 'R&D and Productivity Growth: Panel Data Analysis of 16 OECD Countries', 2001; D. Guellec and B. Van Pottelsberghe de la Potterie, 'From R&D to Productivity Growth: Do the Institutional Settings and the Source of Funds of R&D Matter?', *Oxford Bulletin of Economics and Statistics* 66, no. 3 (2004): 353–78.

[7] See Salter and Martin (2001) for three general ways of collecting data on the relationship between economic benefits and publicly funded research.

[8] A Salter and B. Martin, 'The Economic Benefits of Publicly Funded Basic Research: A Critical Review', *Research Policy* 30, no. 3 (2001): 509–32.

[9] Guellec and de la Potterie, 'R&D and Productivity Growth'; Guellec and Van Pottelsberghe de la Potterie, 'From R&D to Productivity Growth'.

[10] V. Sena, M. Hart, and K. Bonner, 'Innovation and UK High-Growth Firms', NESTA working paper (London: NESTA, n.d.).

[11] M. Coccia, 'What Is the Optimal Rate of R&D Investment to Maximize Productivity Growth?', *Technological Forecasting and Social Change* 76, no. 3 (2009): 433–46.

GDP targets are also, however, a topic of discussion, see M. Mazzucato and W. Lazonick, 'Limits to 3% R&D Target', FINNOV Position Paper, 2010.

Countries differ significantly in the type of R&D they fund and conduct and in the institutional arrangements for R&D.[12] For some countries, investment in R&D is largely made through the private sector, while for other countries most R&D investment is made through public universities. These differences limit the ability to generalise from international comparative studies. These caveats will be further explored in the specification of the research problem and the methodology in Chapter 2.

'Absorptive capacity' is another important contextual factor when considering the impact of R&D on GDP. While the term absorptive capacity can be interpreted in different ways, the definition outlined by Allas[13] is used in this study, which defines it as the ability to 'recognise the value of new, external information, assimilate it and apply it to commercial ends'. In short, it is the ability to recognise and run with a new idea.

Absorptive capacity relies heavily on the supply of science, technology, engineering, and mathematics (STEM) graduates and other graduates in a country, and therefore differs substantially between countries. Absorptive capacity is an important determinant of a country's capacity to innovate and work with R&D; and growing and maintaining absorptive capacity is an important part of R&D performance from the perspective of a country's economy. As absorptive capacity largely relates to people, the indicators used to estimate absorptive capacity will centre around the number of researchers in a country.

1.2. Specification of the research questions

Despite the broad associations between R&D spending and GDP, questions remain around how particular increases or decreases in funding relate to changing levels of research quality. These questions rely on detailed data of research quality rather than impacts on GDP or other downstream indicators, and therefore require a different approach from studies that explore the economic impacts or benefits of research. This study investigates the relationship between research spending and research quality, exploring two key research questions as specified by the Department for Business, Innovation and Skills (BIS):

- What is the relationship between spending and research performance?
- What are the nonlinearities in this relationship?

This section reviews the research questions posed by BIS, how they are understood, and ways in which they can be addressed. This provides the context for discussion of the research problem and methodology in Chapter 2.

[12] National Science Board, 'Science and Engineering Indicators 2014' (Arlington: NSB, 2014).

[13] Allas, 'Insights from International Benchmarking of the UK Science and Innovation System'.

1.2.1. Research question 1: What is the relationship between spending and research performance?

There are a number of different ways that research performance can be defined and measured. The academic performance of research is typically measured in terms of the quality of the research; traditionally through peer review, but also through bibliometric methods that use the level of citation by others as a proxy for quality. Other measures of academic performance are related to capacity building, such as numbers of PhD candidates trained; advancement of the careers of those involved in the work; or creation of new tools, techniques, methods or infrastructure for research. To measure the reach of research, altmetrics have started to be used in addition to other measures around media mentions and dissemination activities.[14]

Research performance can also be measured by looking at the impacts of research further downstream, such as economic benefits or benefits to society through improved health, security or well-being. Data on these are typically more difficult to collect as they often require primary data collection through surveys, case studies and interviews. However, there are proxies in existing datasets that can be used to observe these outcomes, particularly on the economic side, such as numbers of patents or growth of high tech and scientific sectors in the country.

In this study, research performance will largely be considered in terms of its academic impact as measured using a set of standard bibliometric indicators. While this is a widely used approach, it does have several important limitations. First, the downstream research outcomes are of most interest to the taxpayer, and consequently the government, rather than the academic impacts. A simplifying assumption may be that higher quality academic research is more likely to result in the achievement of these wider impacts, however, the evidence on this is not clear. In recent RAND Europe studies looking at the impacts of research over the last 25 years, primarily through case studies, there is no clear evidence of a correlation between work that has a high output of academic knowledge produced and the downstream impact on the economy and society.[15] Therefore, although measures such as the field (and year) normalised citation score and the number of highly cited publications are established and important measures of academic merit, they do not necessarily provide an effective proxy for the wider impact of research.

Second, bibliometrics have some considerable caveats and limitations to their usefulness. For example, they are not appropriate to use in some research fields because of the way in which research is typically reported in those fields (for example, through books rather than journal articles). These caveats and limitations are further explored in Chapter 2.

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[14] Adam Dinsmore, Liz Allen, and Kevin Dolby, 'Alternative Perspectives on Impact: The Potential of ALMs and Altmetrics to Inform Funders about Research Impact', *PLoS Biology* 12, no. 11 (2014): e1002003.; M. Taylor, 'The Challenges of Measuring Social Impact Using Altmetrics', *Research Trends*, no. 33 (2013).

[15] S. Wooding et al., *Project Retrosight Understanding the Returns from Cardiovascular and Stroke Research: The Policy Report* (Cambridge: RAND Corporation, 2011); S. Wooding et al., *Mental Health Retrosight: Understanding the Returns from Research (lessons from Schizophrenia): Policy Report* (Cambridge: RAND Corporation, 2013).

Finally, the fundamental underpinning of the use of bibliometrics as a measure of research quality is that citation is an appropriate proxy for quality. This can be appealing as it draws on the 'wisdom of the crowds' to assess the quality of research and effectively harnesses the perspectives of peers in the research field in question. However, citations can happen for many reasons and may be due to the novel use of a new method in a field or to point out the flaws in a piece of work. It is possible for an article to receive many citations because it is widely criticised in the literature. As such, the underlying assumption that citation is a proxy for quality, although widely tested and largely accepted, should be considered. However, as citations are one of the few objective and widely collected data available that serve as a proxy for quality, it is important to include them in this study.

1.2.2. Research question 2: What are the nonlinearities in this relationship?

To explore this question, 'nonlinearities' or 'disproportionate effects' must be clarified. Two nonlinear disproportionate effects are identified as being of particular interest for this study. The first are 'cliff-edges': points where a small decrease in funding results in a significant decrease in some or all measures of performance. The second are 'take-off points': points where a small increase in funding improves performance significantly. These are equivalent and in both cases denote points where a small change in funding results in a step change in some (or all) measures of performance.

However, these step changes are only one type of nonlinearity that may be present. Even where there is not a step change, there may be a levelling off or an exponential growth in performance measures associated with changes in funding at different funding levels. Both cases are part of a larger number of outcomes that can theoretically be derived as consequences of changes in spending. At the most basic level, three outcomes for a change in spending can be identified, which in the case of increases and decreases in spending provides six options, of which two are less likely (Table 1). While the interest of this study is in take-offs and cliff-edges, it is important to understand that these are only two options out of a range of possible outcomes following a change (or even stability) in funding.

Table 1: Research spending and performance options

Increase in spending	Increase in performance: step-change (e.g. take-off) or gradual
	Continuation of performance
	Decrease in performance: step-change or gradual (unlikely)
Decrease in spending	Increase in performance: step-change or gradual (unlikely)
	Continuation of performance
	Decrease in performance: step-change (e.g. cliff-edge) or gradual

The cases of cliff-edge and take-off are explored in this study through in-depth case studies. In these case studies different data sources are used to understand exactly how a change occurred and what the consequences were. The exact methodology underlying the case studies is explained in Chapter 2.

2. Research problem and methodology

2.1. What is research and what is innovation?

Terms such as research, performance and innovation are used frequently, often without clarification of their specific meaning, and as such it is useful to indicate which areas fall within the remit of this work and which areas are beyond the realm of this study.

2.1.1. Research

Research or R&D is the central focus of this study. The *Frascati manual* from the OECD defines R&D as:

'Research and experimental development (R&D) comprise creative work undertaken on a systematic basis in order to increase the stock of knowledge, including knowledge of man, culture and society, and the use of this stock of knowledge to devise new applications.'

Research work can take place in both public and private institutions and is generally conducted in dedicated institutions, such as universities and laboratories. Not all research work is the same, and within R&D a common distinction is often made between basic research, applied research and experimental development. These three sub-categories are defined by the *Frascati manual* as follows[16]:

'**Basic research** is experimental or theoretical work undertaken primarily to acquire new knowledge of the underlying foundation of phenomena and observable facts, without any particular application or use in view.

Applied research is also original investigation undertaken in order to acquire new knowledge. It is, however, directed primarily towards a specific practical aim or objective.

Experimental development is systematic work, drawing on existing knowledge gained from research and/or practical experience, which is directed to producing new materials, products or devices, to installing new processes, systems and services, or to improving substantially those already produced or installed.'

This study aims, where possible, to take these differences in research activities into account by disaggregating data into the respective categories. However, the *Frascati manual's* breakdown still conceals

[16] Frascati Manual OECD, 'Proposed Standard Practice for Surveys on Research and Experimental Development' (Paris: OECD, 2002).

a lot of variety within research, for example, engineering is different from medicine, which in turn is very different from pure mathematics. The differences between fields has been taken into account as much as possible to increase the accuracy of this study. The sections below indicate where such disaggregation is and is not possible.

2.1.2. Innovation

In order to clearly define the scope and subject matter of this study it is useful to distinguish, at least conceptually, R&D from innovation. While rigid boundaries between the two cannot be identified in practice, the conceptual difference should be addressed as it has implications for the design of this study. The OECD's Oslo manual defines innovation as:

'Technological product and process (TPP) innovations comprise implemented technologically new products and processes and significant technological improvements in products and processes. A TPP innovation has been implemented if it has been introduced on the market (product innovation) or used within a production process (process innovation). TPP innovations involve a series of scientific, technological, organisational, financial and commercial activities. The TPP innovating firm is one that has implemented technologically new or significantly technologically improved products or processes during the period under review.'[17]

Innovation performance is generally measured through a different set of indicators than R&D performance. Early conceptions of innovation systems meant that the initial innovation indicators were closely tied to R&D inputs and outputs; ranging from investment amounts in R&D, numbers or researchers, to bibliometric measures and the number of patents produced in a particular location.[18] Given the increased understanding of the complexity of innovation, and a move away from innovation as a strictly technology-based process to include social and behavioural processes and outcomes, it is now clear that such early indicators were inadequate and cannot fully capture an innovation system.

2.1.3. Focus on R&D

As the focus of the research specified by BIS is on research, this study will not directly investigate the wider innovation system. The indicators of performance listed by BIS and the spending categories outlined are oriented towards R&D. This focus does not imply that innovation is unrelated or unimportant; it simply helps to establish the scope of the study. The delineation of the subject matter is useful to specify as it guides the methodology for the study. The data and indicators to measure either R&D or innovation can differ substantially and to ensure the rigour and consistency of the study it is important to clearly define the topic of the study, in this case R&D.

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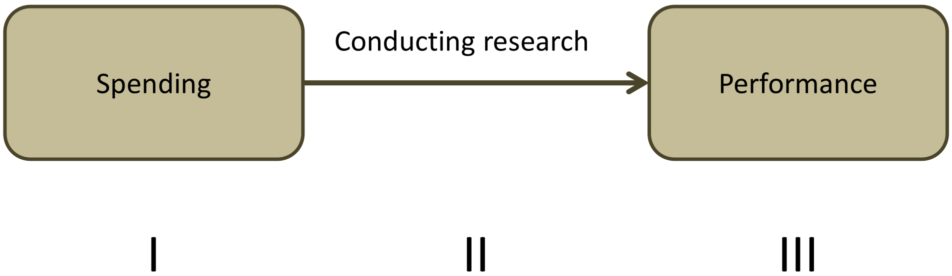
[17] Statistical Office of the European Communities, *Oslo Manual: Guidelines for Collecting and Interpreting Innovation Data*, 4 (Paris: OECD, 2005).

[18] C. Freeman and L. Soete, 'Developing Science, Technology and Innovation Indicators: What We Can Learn from the Past', *Research Policy* 38, no. 4 (2009): 583–89.

2.2. Clarification of the research problem

The elements of the research problem can be outlined in a simple figure that shows the starting point of the study: the relationship between research spending and research performance. The link however, is not as simple as it seems, and for each stage of the relationship several complexities and caveats need to be considered in order for the study to be accurate and rigorous. Three stages are identified in this process, as set out in Figure 1 below: research spending, conducting research, and research performance. Each of these will be discussed in turn, both to highlight the caveats and complexities, and to clarify the scope of this study.

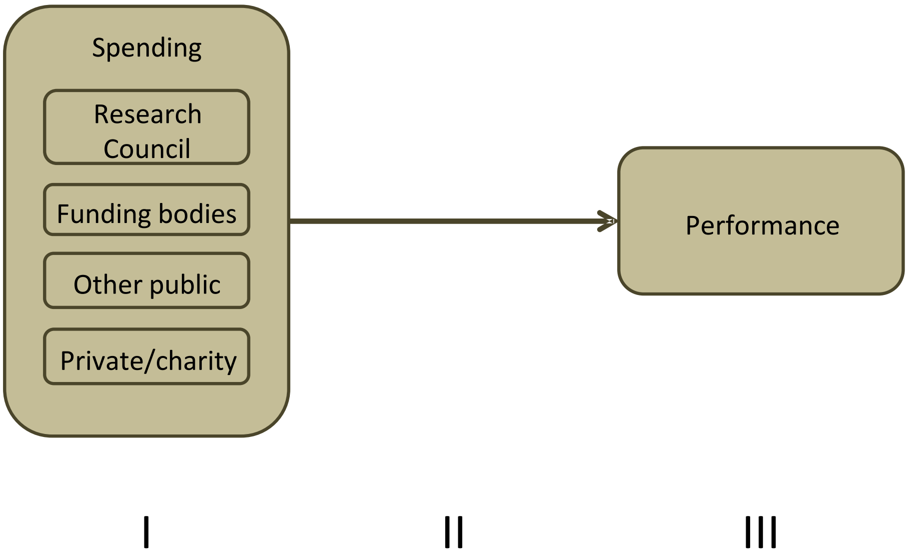
Figure 1: Simple representation of research spending and performance



2.2.1. Stage I – Spending

With the first stage, spending on research, the initial complexity lies in the different sources of research spending that can be identified. There is a difference between sectors, as government, the private sector (or business), charities and other public and private organisations can invest in research. Furthermore, different streams of funding exist within most governments. In the United Kingdom, for example, multiple ministries fund research (e.g. Department of Health, Ministry of Defence, Department for Business, Innovation and Skills), and within these ministries there are multiple bodies responsible for research funding. The primary focus for this study will be on research funding flowing from BIS, however, there are caveats that complicate a straightforward analysis of the relationship between funding from BIS and research performance.

Figure 2: Spending diversity



The first caveat follows directly from the diversity of funding streams available. Research projects are often funded through a number of different streams, and even where there is only one funding stream, it is very difficult to disentangle and attribute research outcomes (such as journal articles) to particular streams of funding. Attribution is possible through, for example, examining individual papers to analyse funding acknowledgements. However, such analysis is beyond the remit of this study, particularly as funding acknowledgements are not universally available on publications and it cannot be assumed that researchers are aware of and acknowledge all of their different funding streams.[19]

It is therefore not possible to separate a set of publications that result from government funded research to compare to government funding, and another set of publications relating to research funded by industry, for example. All that can be deduced from the available data is the contribution that different sources of funding have made to the total investment in research in a country. Within this study, different analyses are run where, for example, the business share of research funding is included or excluded. For each analysis it will be noted which streams of funding are in- or excluded.

The second caveat relates to the organisation of research funding. The system of research funding in the United Kingdom relies on what is known as the dual support system, in which there are two separate streams of research funding. The first stream of funding, known as quality-related (QR) funding, flows

[19] R. Costas and T. Leeuwen, 'Approaching the "reward Triangle": General Analysis of the Presence of Funding Acknowledgments and "peer Interactive Communication" in Scientific Publications', *Journal of the American Society for Information Science and Technology* 63, no. 8 (2012): 1647–61.

through UK Funding Bodies[20] and is based on a research quality assessment, the most recent of which is the Research Excellence Framework (REF) 2014.[21] The second stream of funding flows through the Research Councils UK and is based on peer-reviewed grant applications.[22] As with the different streams of funding, the current analysis is not be able to separate these funding streams, which in general are designed to be interconnected and interdependent.

The third caveat, suggested by experts consulted at the start of this study, is that the setup of the funding system itself may be responsible for research excellence. This means that even for similar amounts of funding, the way in which research funding is organised in the United Kingdom may lead to better outcomes than in other countries where research funding is organised differently. This relates to a wider trend towards more competitive research funding that has been observed in many Western research funding systems.[23] The United Kingdom is generally recognised as the most competitive research funding system in Europe, however other countries, such as Italy, are also developing in this direction.[24] The option to construct an indicator that captures these differences is explored in Chapter 6, however it is concluded that the data are not sufficient to include an indicator on the share of competitive funding in the analysis. The methodology explains how some of these effects and country differences will be accounted for by the 'country fixed effects' in the econometric model.

2.2.2. Stage II – Conducting research

The second stage of understanding the relationship between research spending and performance is conducting research, where there is a degree of diversity that needs to be recognised. Research differs substantially between disciplines and apart from the obvious differences in subject and methodology, there exist different funding arrangements and different time-lags between inputs (e.g. funding) and outputs (e.g. papers). Some disciplines may be, for example, more dependent than others on funding through charities, and producing outputs may take longer in some disciplines than others.

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[20] Under funding bodies we list: Higher Education Funding Council for England (HEFCE), Higher Education Funding Council for Wales (HEFCW) and the Scottish Funding Council (SFC) and for the Department for Employment and Learning (DEL).

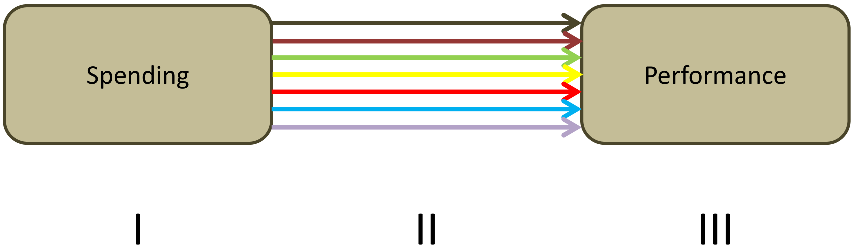
[21] Striking a Balance - dual support, http://www.parliament.uk/business/publications/research/briefing-papers/POST-PN-99/striking-a-balance.

[22] Dual Funding Structure for Research in the UK: Research Council and Funding Council Allocation Methods, and Impact Pathways, https://www.gov.uk/government/publications/dual-funding-structure-for-research-in-the-uk-research-council-and-funding-council-allocation-methods-and-impact-pathways.

[23] A. Geuna and B. Martin, 'University Research Evaluation and Funding: An International Comparison', *Minerva* 41, no. 4 (2003): 277–304; D. Hicks, 'Performance-Based University Research Funding Systems', *Research Policy* 41, no. 2 (2012): 251–61; B. Jongbloed and H. Vossensteyn, 'Keeping up Performances: An International Survey of Performance-Based Funding in Higher Education', *Journal of Higher Education Policy and Management* 23, no. 2 (2001): 127–45; J. Wang and D. Hicks, 'Policy Screening by Structural Change Detection: Can Policies Effectively Boost Research System Performance?', in *Proceedings of 17th International Conference on Science and Technology Indicators*, vol. 2, 2012, 815–25.

[24] Hicks, 'Performance-Based University Research Funding Systems'.

Figure 3: Research diversity



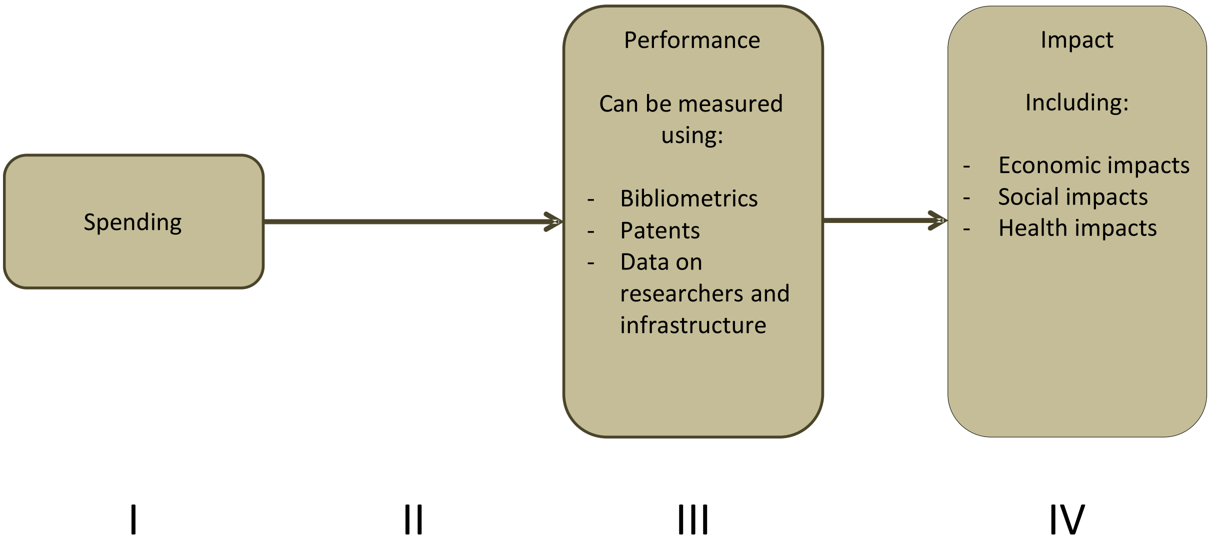
A caveat that follows from this inherent diversity is that in the cross-country comparison, the aggregate data do not take these differences into account. Although there is data on the performance of different research areas, there is no way to link these to particular funding streams. The exploration of disciplinary or research area differences can only be done at the national level, for example in the United Kingdom an attempt can be made to disaggregate disciplines through an analysis of the funding streams of different Funding Bodies and Research Councils.

It is important to note the changing nature of the research landscape within and between countries. Research fields can increase and decrease in importance, new fields can emerge, and researchers can move between disciplines and countries. Research is also conducted in a wider socio-economic context: the quality and availability of education, the wider jobs market, economic circumstance affecting industry priorities, and many other factors may have an influence on the performance and potential of research in a country. The presence, and, as much as possible, the importance of these exogenous factors will be considered in both the quantitative and qualitative elements of the work conducted here. However as this is not the key focus of the study these issues will be considered as caveats to the core findings rather than explored in their own right.

2.2.3. Stage III – Performance

The third stage of the relationship is research performance. Research performance can be defined in a number of ways, but the focus of this study is on both the quality of the research produced and the human capital and research infrastructure developed or maintained. Performance therefore covers more than just direct outputs (e.g. articles) and encompasses capacity building in the form of personnel and infrastructure.

Figure 4: Performance diversity



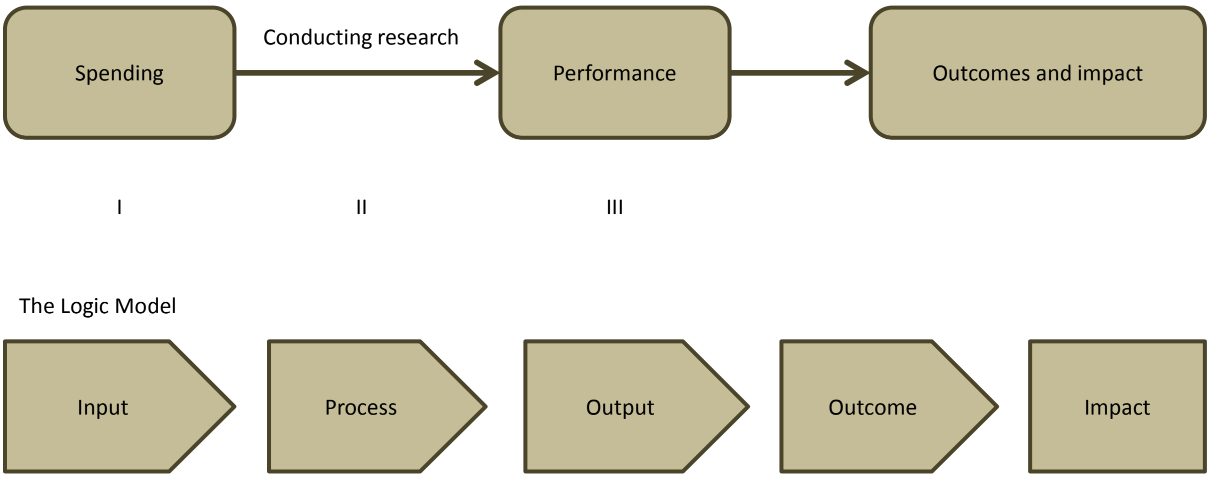
Not all elements of performance can be fully captured through the bibliometric and other routine quantifiable data available. First, different disciplines produce different kinds of outputs and in some disciplines inventions, applications, or medicines may be the primary output rather than publication of articles. Such outputs are sometimes, but not always, captured by patents and articles, however a substantial part of research performance is missed using the data available at the aggregate level. Second, further inherent limitations to bibliometrics will be outlined in the methodology. Third, the current indicators of performance do not yet capture wider impacts that can arise from research.

2.2.4. Focus on research quality, not (yet) impact

The recent Research Excellence Framework, coordinated by the Funding Councils in 2014, increased the debate around the notion of impact by including the impact of research as one of the categories for ranking and funding decisions for universities in England. Given the vast attention to 'impact', it is useful to briefly clarify the relationship between the concept of 'research quality' used in this study and 'impact'.

Impact is the stage that follows the production of research outputs. Through research, a number of products are produced, such as publications. In this study, the focus is on the quality of these research outputs, as measured by bibliometric and other indicators outlined below. These outputs can lead to changes in the economy, in health, in society or anywhere else. Such changes are generally captured under the notion of 'impact'. Using a logic model, which is a commonly used evaluation tool to represent the steps taken to achieve certain goals, the relationship between outputs and impacts are clarified. In this study, performance measures reflect the output from research, after which impacts may occur.

Figure 5: The logic model from spending to impact



Apart from the fact that impacts can be difficult to measure, there is another reason why this study focuses on outputs, namely time-lags. It takes time for research to yield outputs and it takes even more time for impacts to be realised.[25] In order to pick up signals of change as soon as possible, whether cliff-edge or take-off, it is useful to work with the data most readily available. As data on outputs is easier to collect and is available sooner, we currently focus on outputs. The notion of time-lags however, has further implications that require attention.

2.2.5. Importance of time-lags

Time-lags refer to the time it takes for investment in research (inputs) to translate into the conduct of research (process), then into the products of research (outputs), and eventually result, hopefully, into impact. Investments made in year one will only yield research outputs a few years down the line as conducting research and publishing takes time. This means that the analysis of investment in year one cannot directly be compared to the outputs of year one as these outputs are not the direct result of these investments, but the results of investments made in previous years.

In order to compare the relationship between investments, or spending and outputs, it is necessary to understand how long, on average, it takes for research spending to result in research outputs. While there have been some studies into such time-lags, as will be discussed below, there is not much clarity on the length of the time-lag between spending and outputs. An important aim of the econometric analysis, therefore, is to identify what the time-lags are between spending and different types of research outputs.

The importance of taking time-lags into account can be illustrated through the example of Canada. Research spending in Canada changed between 1996 and 2012, as is visible from the left pane of Figure 6. Spending increased in the first four years of the period (green), however increases in publications only

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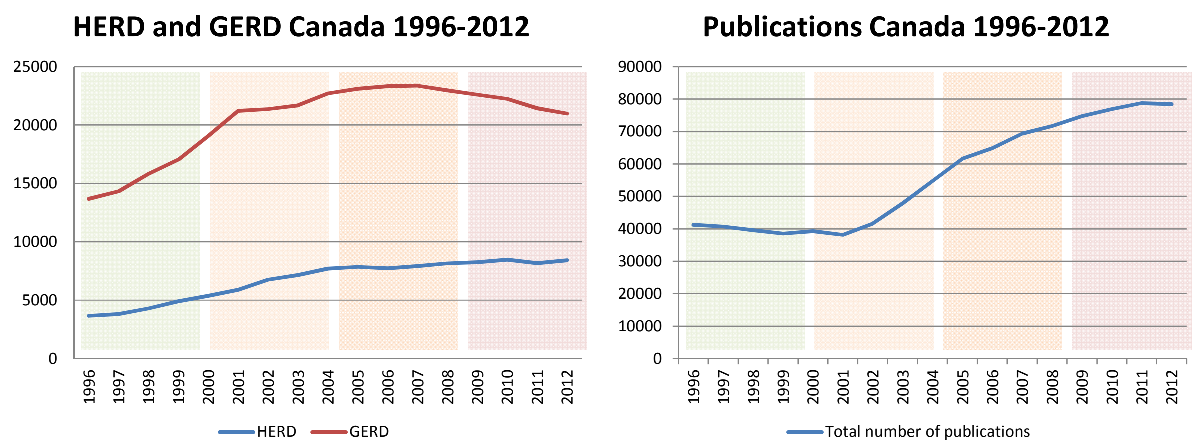
[25] For medical research, the time-lag to impact has been estimated to be around 17 years. See: Z. Morris, S. Wooding, and J. Grant, 'The Answer Is 17 Years, What Is the Question: Understanding Time Lags in Translational Research', *Journal of the Royal Society of Medicine* 104, no. 12 (2011): 510–20.

follow a few years later and do not yet occur in the green pane on the right. Conversely, when research spending stagnates and decreases in the final eight years, the slow down in publications is also delayed and only starts to become visible towards the end of the available data.

Figure 6: Apparent time-lags in Canada



2.3. Research question 1: modelling scientific production through an econometric approach

There are only a few studies identified that have empirically examined the relationship between inputs, such as funding, and research output or performance at the national level.[26] Crespi and Geuna provide an elaborate econometric analysis of time-lags and possible 'spill-overs' of changes in researcher funding on research output. They examine both publications and citations and estimate time-lags to be around five to six years.[27] Auranen and Nieminen investigate how the funding environment of university research differs across countries and whether those differences translate into variances in publication performance (i.e. efficiency of university research, defined as the volume of publications divided by the level of funding).[28] Similar studies of performance and efficiency have been conducted by May, King, Leydesdorff and Wagner, and Wendt et al.[29] Many of these studies, with the exception of May and King, confine

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[26] For an overview of micro-level and macro-level studies see: A. Ebadi and A. Schiffauerova, 'Impact of Funding on Scientific Output and Collaboration: A Survey of Literature', *Journal of Information & Knowledge Management* 12, no. 04 (2013).

[27] G. Crespi and A. Geuna, 'An Empirical Study of Scientific Production: A Cross Country Analysis, 1981–2002', *Research Policy* 37, no. 4 (2008): 565–79.

[28] O. Auranen and M. Nieminen, 'University Research Funding and Publication performance—An International Comparison', *Research Policy* 39, no. 6 (2010): 822–34.

[29] D. King, 'The Scientific Impact of Nations', *Nature* 430, no. 6997 (2004): 311–16; L. Leydesdorff and C. Wagner, 'Macro-Level Indicators of the Relations between Research Funding and Research Output', *Journal of*

themselves to an assessment of efficiency on the basis of the number of publications a country produces. As such, they do not take into account any differences in the quality of these papers (e.g. in citations), nor are country differences accounted for in great detail.

Analysis by Wang and Hicks aimed to identify structural changes in either research funding (Higher Education Research and Development, HERD) or research output (publications) in order to determine whether policy changes affecting research funding have a visible effect in the data. The study was carried out in five countries (Australia, Germany, Canada, the United Kingdom, the United States), however few structural changes were identified.[30]

Apart from the literature on research performance using publications as the outcome variable, there is a literature on patents that examines the relationship with funding, with the seminal paper being Hall et al.,[31] which investigated whether there is a lag in the patent and research relationship at the level of the firm. The main finding of the study is that once differences in the propensity to patent across firms is controlled for, there is direct evidence of a contemporaneous effect of spending on patent activity. The effect is U-shaped, meaning that after three to five years the impact of funding becomes stronger again. A similar pattern was found more recently by Blundell et al.[32] and Montalvao.[33] There is however, no wider consensus in the literature on what the relationship between research and patenting looks like.

While a systematic review of the literature was not part of this study, a scoping of the literature suggests that its approach to the econometric analysis could contribute to the existing literature in several ways. First, the study systematically assesses the relationship between different levels of, and changes to, research funding on performance using econometric models. Second, as well as the number of publications, the study includes additional bibliometric outcome measures, such as number of citations and number of highly cited papers (the specific measures used are defined in more detail below). Third, in order to account for country differences a number of indicators around different characteristics of the research system are constructed.

In addition to the analysis across countries, some analysis in this study focuses solely on the United Kingdom where the differences in funding and performance between research fields are investigated. This allows for a more detailed exploration of some of the characteristics of the research in a UK specific context.

Informetrics 3, no. 4 (2009): 353–62; R. May, 'The Scientific Wealth of Nations', 1997; K. Wendt et al., 'Challenges in Cross-National Comparisons of R&D Expenditure and Publication Output', *Indicators* 2011, no. 2 (2012).

[30] Wang and Hicks, 'Policy Screening by Structural Change Detection'.

[31] B. Hall, Z. Griliches, and Jerry A. Hausman, *Patents and R&D: Is There a Lag?* (National Bureau of Economic Research Cambridge, Mass., USA, 1984), http://www.nber.org/papers/w1454.

[32] R. Blundell, R. Griffith, and F. Windmeijer, 'Individual Effects and Dynamics in Count Data Models', *Journal of Econometrics* 108, no. 1 (2002): 113–31.

[33] J. Montalvo, 'GMM Estimation of Count-Panel-Data Models with Fixed Effects and Predetermined Instruments', *Journal of Business & Economic Statistics* 15, no. 1 (1997): 82–89.

The remainder of this chapter outlines the approach in more detail, including data collection and preparation, the econometric analysis, and limitations and caveats around the approach.

2.3.1. A simple model of scientific production

Drawing on the seminal work by Griliches,[34] a simple knowledge production function can be written as follows:

$Y = F(X, K, u)$

This function relates a measure of scientific output *Y* to inputs *X*, *K* and *u*. *X* represents an index of inputs, such as research labour; *K* represents a measure of the current level of scientific knowledge, determined by current and past R&D expenditures; and *u* represents all other unmeasured determinants of output and productivity. The production function can be specified as Cobb-Douglas and, in line with Crespi and Geuna (2005),[35] it can be assumed that the unmeasured factors *u* are random after the introduction of a time trend. This seeks to represent the systematic component of the unmeasured factors and rewrite the function as:

$$Y_{it} = C_i X_{it}^{\propto} K_{it}^{\beta} e^{\theta t + u_t}$$

In this rewritten function, *C* is a non time-varying factor at the country level i (e.g. inherent research productivity effect); e represents the natural logarithm base; and ∝, β and θ are the parameters the study's approach seeks to estimate.

There are a few challenges that need to be taken into account when measuring the level of scientific knowledge K.[36] First, the research process takes time. From the funding of research to the actual output (e.g. publications) several years can elapse and current R&D expenditures may not have an effect on current research productivity.

Second, past R&D investments depreciate and become less efficient and therefore the net stock of knowledge capital is not equal to the gross level of current or recent resources invested. Determining the rate of depreciation of knowledge capital is relatively complex. Private knowledge capital may depreciate more rapidly when, for example, products and processes from close competitors reach the market and become close substitutes. Much less is known about depreciation of the public stock of knowledge, however it may be assumed that such knowledge is useful for a long time period and therefore subject to lower rates of depreciation. This can be indirectly controlled for by including an extensive lag length in the estimated models, but the study is not able to identify the depreciation rate directly.

Third, the stock of knowledge within a country is unlikely to be exclusively derived from its own research activities, but is also affected by the scientific knowledge of other countries. This is called a 'spillover'

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[34] Zvi Griliches, 'Issues in Assessing the Contribution of Research and Development to Productivity Growth', *The Bell Journal of Economics*, 1979, 92–116.

[35] G. Crespi and A. Geuna, *Modelling and Measuring Scientific Production: Results for a Panel of OECD Countries*, SPRU Electronic Working Paper 133 (Brighton: SPRU, 2005).

[36] Griliches, 'Issues in Assessing the Contribution of Research and Development to Productivity Growth'.

effect. It is important to stress that the analysis in this study will focus solely on the issue of time-lags and will not aim to estimate spillovers. The study estimates the scientific production function in its more accessible and prominent linear (log) form, which allows for the output elasticities to be determined:

$$y_{it} = c_i y_{it} = c_i + \propto x_{it} + \beta\, k_{it} + \theta t + u_t$$

The lower case letters of y, x, and k represent the natural logarithm.

This analysis mainly focuses on the relationship between research outputs and different determinants, as outlined in the equation above. In doing so, it seeks to pay special attention to the time-lags between research spending and performance. To capture the optimal lag structure, the study uses a polynomial distributed lag model, as suggested by Crespi and Genua.[37] To this end, the study replaces k_{it} with a series of lags (denoted with q) and tries to determine the efficient lag structure using ordinary least squares (OLS).

There is a challenge that needs to be considered with q lags in the model when the data sample is relatively small. For example, if there are data for observations from t=1 to T, then the earliest observation that can be included in such a model is t = q+1. This is because data are required for the q periods before the start of the sample for the lagged terms on the right-hand side of the equation to be included. Therefore, T-q observations would be available to estimate q+2 coefficients, which affords T-2q-2 degrees of freedom. Every time the time-lag is lengthened by one year, two degrees of freedom are lost. This should not pose a problem as long as the sample is large relative to the length of the lag distribution.

Unfortunately, economic theory does not suggest a clear answer on the length of the lag structure, which means that it needs to be determined empirically. To search for the optimal lag length we will start by using a large number of lags and then subsequently reduce them year on year down to zero. For each reduction we will evaluate information criteria designed to measure the amount of information lost due to the omission of an additional lag, with the amount of information gained as a result of the greater degrees of freedom available. To that end we use the Akaike information criterion (AIC) and the Schwartz/Bayesian information criterion (SBIC).[38] Both measures are goodness-of-fit measures of the same type as the R-squared.

2.3.2. Data collection and preparation

Three main datasets required to conduct the analysis in this study have been identified. The first is spending data, which serves as the input in the study's model. The second is measures of research performance, which serves as the output measure. Finally, data sources for any control variable that may be used in the analysis must be considered.

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37 Crespi and Geuna, 'An Empirical Study of Scientific Production'.

38 See: Ibid.

Spending data

For comparative measures on research expenditure across countries, this study draws on the OECD's Main Science and Technology Indicators (MSTI). A variety of data from the *Data Portal for the UK Research Base 2013* report are also used. This portal includes data on a large set of countries from 1996 to 2012, with corresponding detailed information on research expenditures, such as Gross Domestic Expenditures on Research and Development (GERD), Expenditure on Research and Development in the Business Enterprise Sector (BERD), Government Intramural Expenditure on Research and Development (GovERD), and Expenditure on R&D in the Higher Education Sector (HERD). For the in-country analysis in the United Kingdom, the UK science, engineering and technology (SET) statistics (2013) compiled by BIS is used, as well as UK Funding Bodies data for QR funding for 2000-2015, provided by BIS.

Performance data[39]

Data on research performance are largely taken from a bibliometric database provided by BIS. The data, prepared by Elsevier, cover the years 1996 to 2012 and are from the Elsevier maintained Scopus database.[40] They include a large number of countries (244) and contain various research performance indicators by subject area and country. The main performance indicators used in this study are:

Publications – the raw number of publications per country and by subject area is included as a direct indicator of the volume of publications in a country.

Field Weighted Citation Impact (FWCI) – the FWCI is an indicator of the number of citations an article has received relative to the average number of citations for the subject area, publication year and publication type (e.g. article, letter). The indicator is normalised so that a score of one indicates a number of citations equal to the world average for the subject area. A score above one implies a higher number of citations compared to the world average, and a score below one the opposite. For aggregate units, such as countries, the FWCI scores of individual articles can be combined to provide a single FWCI for a country in a given year.

Top 1%, 5%, 10% (highly cited papers) - the Top 1% (and 5% and 10%) refers to the number of publications that fall within the top percentiles of most highly cited articles. The Top 1% thus covers the one per cent of all publications that received the highest number of citations. Articles falling within the top percentages are generally considered to constitute 'research excellence'.

This study will add data on the number of students completing their PhDs as a measure of capacity building within the area of research performance. These data are available from the OECD as 'Graduates from advanced research programmes'.

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[39] For a useful recent review of bibliometric indicators for research evaluation see: P. Wouters et al., 'The Metric Tide: Literature Review (Supplementary Report I to the Independent Review of the Role of Metrics in Research Assessment and Management)' (HEFCE, 2015).

[40] Elsevier, *International Comparative Performance of the UK Research Base – 2013: A Report Prepared by Elsevier for the UK's Department of Business, Innovation and Skills (BIS)* (Amsterdam: Elsevier, 2013).

Caveats and limitations of bibliometrics[41]

The first limitation refers to the analysis and interpretation of citations. While citations can be interpreted as a reflection of the utility of articles, i.e. their usefulness to research, they cannot, without the proper context, be taken as a direct measure of quality. There could be various explanations, aside from the quality of an article, for why publications have either high or low numbers of citations, even in the case of normalised citation scores that take differences by academic fields into account. A recent article in Nature illustrates this point through an exploration of the 100 most cited articles of all time.[42]

A second and more general limitation of bibliometric analysis relates to different publication practices in academic fields. Bibliometrics is based on published articles and only covers a marginal amount of books and book chapters, which may be important research outputs in some fields (in particular the social sciences and humanities). Such publications may therefore be overlooked by a bibliometric analysis. When interpreting bibliometric results it is important to be aware of this possible bias. Furthermore, research outputs in some disciplines are not focused on publications, and outputs such as interventions or applications are not captured if they have not been described in a published article. Patents can, to some degree, account for these outputs, however they only cover a part of the total number of innovations, as described below.

A third limitation relates to a possible language bias in bibliometric databases. The majority of journals indexed in bibliometric databases are in English, which means that while internationally there is a trend towards publications in English, publications in languages other than English are less likely to be included. These publications are also unlikely to receive as many citations as English publications due to their smaller audience.

A final limitation is how the citations of articles with multiple authors are counted at the aggregate level. For example, if there is an article with two authors from the United Kingdom and one author from France, there are generally two ways in which the citations can be counted.[43] The first method is full counting whereby all publications of a country are given equal weight, and the United Kingdom and France each receive the full number of citations for this article. The second method is fractional counting whereby less weight is given to publications with collaborators from other countries. In the example given, the article would be given a weight of 0.33 for France. For the analysis at aggregate levels, such as universities and countries, the fractional method has recently been suggested as the preferred method as it does not lead to double counting. The result of full counting is that articles with multiple authors are given more weight in the database and hence the overall FWCI for aggregate units goes beyond the world

[41] For a detailed discussion of the strengths and weaknesses of bibliometrics as a research evaluation method, see: S. Ismail et al., *Bibliometrics as a Tool for Supporting Prospective R&D Decision-Making in the Health Sciences* (Santa Monica: RAND Corporation, 2009).

[42] R. Van Noorden, B. Maher, and R. Nuzzo, 'The Top 100 Papers', *Nature* 514, no. 7524 (2014): 550–53.

[43] For a detailed discussion of full counting and fractional counting, and of counting methods in general see: M. Gauffriau et al., 'Publication, Cooperation and Productivity Measures in Scientific Research', *Scientometrics* 73, no. 2 (2007): 175–214; M. Gauffriau et al., 'Comparisons of Results of Publication Counting Using Different Methods', *Scientometrics* 77, no. 1 (2008): 147–76.

average of one.[44] Fractional counting has been shown to restore the average to one, thus maintaining normalisation.

The data used in this study are based on full counting to be consistent with the data of previous years.[45] As changes to the data cannot be made, the use of full counting needs to be listed as a caveat in the analysis and interpretation of the data.

Limitations of patents

Patents are commonly used as a measure of the innovative potential of research, however, there are some limitations to this measure. First, many fields of research or sectors of application do not lend themselves to patenting. For example, pharmaceuticals are typically patentable in the biomedical and health research field, but changes to health service configuration, which might be equally beneficial in terms of health and/or economic outcomes, is not appropriate to capture through a patent. Furthermore, although a patent may be indicative of originality, it does not give any real information on the utility of an invention or discovery. Many patents are not put into use or may, in some contexts, be used defensively to stifle rather than promote innovation. Nonetheless, they are a measurable proxy that will be considered in this study's analysis, with these caveats taken into consideration

Control variables

In addition to this study's output and input measures, a number of other control variables, as suggested by the model above, are also included. The database (based on OECD data) is used to include the total number of researchers in a given country as a control variable, which can serve as a proxy for the general research capacity in a country. In order to control for the relative development status of a country, GDP per capita data from the Penn World Tables version 7.1 is used.[46]

Data sample

In order to conduct a cross-country analysis to examine the relationship between funding expenditure and research performance, 38 countries for which there is detailed information on GERD (as well as HERD) are included in the study's sample. A detailed country list can be found in Appendix A. The expenditure figures used are expressed in millions of constant US$, as reported by the OECD. The dataset is relatively short and recent, comprising the years 1996 to 2012. Chile is excluded from the sample as the full funding data over the whole time period wasn't available.

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[44] D. Aksnes, J. Schneider, and M. Gunnarsson, 'Ranking National Research Systems by Citation Indicators. A Comparative Analysis Using Whole and Fractionalised Counting Methods', *Journal of Informetrics* 6, no. 1 (2012): 36–43; L. Waltman et al., 'The Leiden Ranking 2011/2012: Data Collection, Indicators, and Interpretation', *Journal of the American Society for Information Science and Technology* 63, no. 12 (2012): 2419–32.

[45] Elsevier, *International Comparative Performance of the UK Research Base – 2013: A Report Prepared by Elsevier for the UK's Department of Business, Innovation and Skills (BIS).*

[46] A. Heston, R. Summers, and B. Aten, 'Penn World Table Version 7.1' (Philadelphia: Center for International Comparisons of Production, Income and Prices at the University of Pennsylvania, 2012).

Country fixed effects

The outline of the research problem in section 2.2 suggests that there are a number of other factors that can influence the relationship between research spending and research performance, such as the share of competitive research funding as a proxy of differences between funding systems. Not all of these factors can be taken into account in the form of control variables, however, they will be accounted for almost entirely through the use of 'country fixed effects'.

There are three main reasons why this study's model uses country fixed effects rather than additional control variables. First, the data availability for a number of the factors identified in section 2.2 is limited, meaning that there would be substantial gaps in the data. Second, given the relatively short time-span of 1996 to 2012 for the analysis, the factors are unlikely to vary a great degree within countries and can be captured by country fixed effects. In Chapter 6, these two points are discussed in detail using all available data for two factors of interest: 1) the share of competitive funding, and 2) the share of basic science funding as part of total funding. A third factor of interest, differences between countries in their most active academic field, is discussed in Appendix A. Third, the full investigation of these factors requires a different research question from those that are focused on in this study.

This study's theoretical model suggests the inclusion of country fixed effects (non-time varying country effects) in the analysis. Such country fixed effects could represent unobserved country level heterogeneity that is generated, for instance, by the presence of local special characteristics in each country's national innovation system. Country fixed effects are included in the model as binary indicator variables.

2.3.3. Limitations of the approach

Although this study's analysis of the relationship between research inputs and research performance has several strengths, including the more in-depth analysis of the time-lag structure, there are some limitations to the empirical approach that need to be considered.

First, it is important to stress that although the suggested empirical approach produces associations between spending and output at the country level, causality cannot be asserted. This is because there are unobservable factors that could drive research spending and performance simultaneously, such as unobserved technology shocks that could confound the estimated parameters. Another issue is reverse causality. For example, if the study measures the impact of research spending on research or skill capacity building (e.g. number of new doctorates), spending may be driven by the number of researchers/doctorates in a country and not vice versa. In essence, the more researchers there are active in a country, the more will be spent on research, which in turn could affect performance. There is no straightforward method to take reverse causality into account. One option could be to find suitable 'instrument variables' that are correlated with research spending but not with performance, creating exogenous variation for spending. Finding suitable instruments is always a challenge and is beyond the scope of this study.

Second, the time period of data available for analysing time-lag structures is relatively short. In order not to lose too many degrees of freedom, the study is restricted in the length of the lags that can be taken into account. Third, and related to the relatively short time series data available, the inclusion of country fixed effects reduces the opportunity to include country-level measures, such as the difference between basic or applied research as determinants of research performance. If these measures do not have much variation over time they will be captured almost entirely by the country fixed effects. As this study is mainly interested in the lag structure of funding, this is not a major problem. However, if further research aimed to analyse the effects of other determinants, it would need to consider a different theoretical motivation and estimation strategy, which is beyond the scope of this study.

Fourth, this study expects the data used to be affected, at least to some extent, by measurement error, which could create a bias to the estimated parameters. This is a common issue in this type of analysis and although addressing the measurement error is beyond the scope of this study, it is important to note its existence.

2.4. Research Question 2: Cases of cliff-edge and take-off

To approach the second research question regarding nonlinearities, a combination of qualitative and quantitative methods were used to conduct case studies of instances that have been labelled from the outset as 'cliff-edge' and 'take-off'. Answering the second research question involved four steps. First, potential cases of cliff-edge and take-off were identified for further investigation. Second, data were collected for each case on research spending and research performance. Third, an attempt was made to understand the mechanisms underlying the relationship between research spending and research performance. And fourth, the case studies were analysed to identify cross-cutting themes.

2.4.1. Step 1: Selection of cases

Cases of cliff-edge and take-off are defined as 'points at which a small change in spending inputs will result in a disproportionate change in research performance'.[47] For cliff-edge cases, the consequences for research performance will be negative, whereas for take-off cases there are signals of substantial positive consequences of changes in spending. Both are equivalent and denote points where there is a step change in some (or all) measures of performance resulting from a small change in funding.

A long list of potential case studies was compiled at the start of the project through consultation with the expert panel, suggestions by contacts at the Research Councils, and reviews of relevant documentation, such as the House of Lords' report on Scientific Infrastructure.[48] Through an internal workshop and consultation with BIS, five cases were selected on the basis of the following criteria:

- Timeline: between 1995 and 2010, in order to allow time for the effects to have become visible, but not so much time that is difficult to identify knowledgeable informants for interviews.
- Unit of assessment: generally a stronger focus on macro and meso units of analysis (e.g. research fields and sectors) rather than micro units of analysis (e.g. specific institutions).
- Academic spread: the cases should cover a range of different fields of research.
- Geographical spread: the cases should aim to ensure a degree of geo-graphical spread.

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[47] BIS (2014) The relationship between R&D spending and research performance, ITQ: RE140150BIS

[48] House of Lords, Science and Technology Select Committee, 'Scientific Infrastructure: 2nd Report of Session 2013–14' (London: House of Lords, 2013).

- Data availability: cases for which data are deemed to be available.

The five cases selected were: air quality; semiconductors; Nuclear Magnetic Resonance Spectroscopy (NMR); soil science; and birth cohort studies. The cross cutting themes emerging from the cases are discussed in detail in Chapter 4.

2.4.2. Step 2: Data collection on spending and performance

To gather data, multiple sources were used to different ends, as summarised in Table 2.

Table 2: Data sources for the case studies

Source	Type of data	Purpose of data
Articles (academic and non-academic)	Articles can provide overviews of the development of a field or sector and shed light on the changes that have taken place.	Articles can be used to provide information both on the spending and on the performance of a field or sector.
Interviews	Interviews with academics, policy makers (e.g. from research councils) and other stakeholders (e.g. industry) provide information on the development of a field or sector and may provide concrete data on spending and performance.	Interviews can be used to understand the narrative around the development of a field or sector. They provide depth and tend to illustrate the complexities involved in understanding a case.
Bibliometric data	Data on publications and citations can provide an indication of the development of a field.	Bibliometrics data can help to show the development of a field in terms of size (e.g. number of publications) and quality (e.g. citations and highly-cited papers).

Twenty-two interviews were conducted across the five case studies. The anonymised list of interviewees is listed in Appendix B.

Three main measures of the effect were used to determine and verify the disproportional effect of the cases of cliff-edge and take-off: human capital, physical capital and research performance. Human capital refers to the 'productive wealth embodied in labour, skills and knowledge',[49] and in the case of research refers to the number, quality and skills of researchers and those involved in the research process. Physical capital refers to the research infrastructure and equipment available to researchers. Research performance refers to the productivity of the field in terms of research outputs (both quality and quantity), and can be measured, for example, by using the bibliometrics measures identified above.

[49] OECD, 'OECD Glossary of Statistical Terms' (OECD, n.d.), http://stats.oecd.org/glossary/.

This study hoped to assess the impact that cases of cliff-edge and take-off have had on research performance by using the sector breakdown in the bibliometric database. However, this has not been possible as the bibliometric data could not be disaggregated to the level of detail required for the case studies. Despite the variety of data sources consulted, this is only one of a number of challenges and complexities that were encountered and identified in the collection of data for the case studies.

2.4.3. Step 3: Understanding the mechanisms leading to certain outcomes

The third step in answering the second research question was attempting to identify the mechanisms that generate nonlinear impacts and to identify associated factors, i.e., characteristics that different cases of cliff-edge and take-off may exhibit and that may be shared across different cases. This can help with understanding why (and if) the disproportionate impact arose.

The case studies also aimed to understand the mechanisms involved. Mechanisms are difficult to define but are commonly understood to constitute the processes that link one event or observation (e.g. a spending change) to another (e.g. a change in human capital).[50] Mechanisms thus represent the path by which the first observation leads to the second observation. They allow for a deeper understanding of the links between these observations, which can be difficult to achieve through econometric analysis. In the case studies, mechanisms are the processes through which spending decisions are transferred or translated into disproportional changes in research capacity and research excellence. These processes can vary from the (dis)investments in capital to hiring/firing of academic staff.

The associated factors and mechanisms have been explored in two ways in this study. First, mechanisms have been the explicit focus of a number of interviews, for example with academics. Through interviews an understanding can be generated of the ways in which a field or sector has been transformed. In addition, three internal workshops with all the project team members were organised to analyse any patterns in the case studies, share learning and discuss emerging findings.

2.4.4. Step 4: Identification and analysis of cross-cutting themes

Cross-cutting themes were identified through several internal team meetings. These were then discussed in-depth during a workshop with the senior advisors to the project. The five cross-cutting themes identified and analysed will be discussed in detail in Chapter 4. The entire methodological 'pathway' of the case studies that has been developed in this study, from identification to analysis, is summarised in Figure 7.

2.4.5. Limitations and caveats of this approach

The analysis here (and also in the quantitative work) depends on the use of historical data, both qualitative and quantitative, and previous experience suggests that there are often challenges in interpreting the implications of findings based on historical data in the present context. For example, the

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[50] P. Hedstrom and R. Swedberg, 'Social Mechanisms: An Introductory Essay', *Social Mechanisms: An Analytical Approach to Social Theory*, 1998, 1–31.

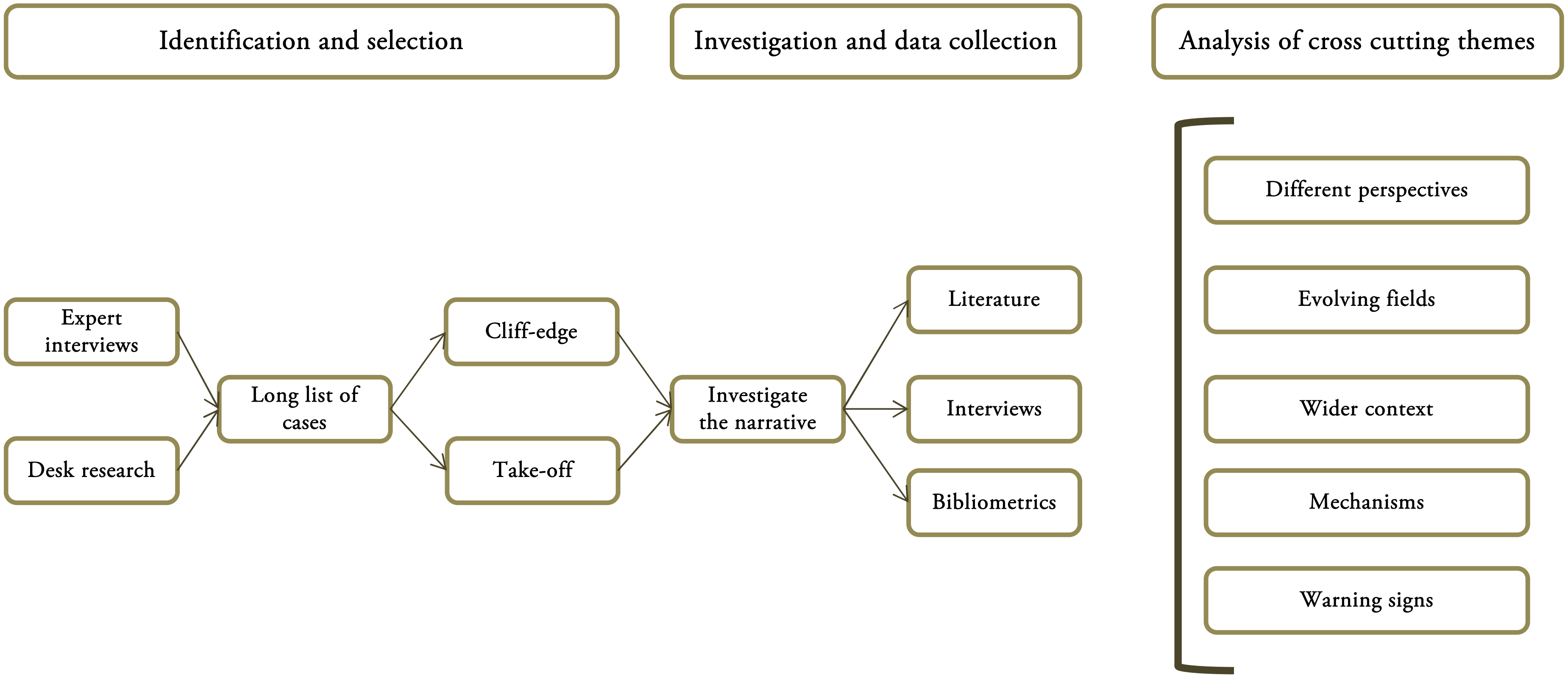
field may have changed over that time, perhaps meaning that new techniques have been introduced that reduce the need for complex equipment and hence remove particular take-off points resulting from funding for investment in equipment or infrastructure. Similarly, it may be that modern approaches are more reliant on complex and expensive infrastructure. In medical research, for example, larger and more expensive trials may be needed to produce statistically significant data on some of the challenging questions that remain to be addressed. Increased international collaboration in such large trials may mean that start-up costs are lower.

There are also potential issues regarding critical mass. RAND Europe is currently undertaking a study into the economies of scale and scope in research that will start to investigate these issues. Historically, the assumption has been that a minimum critical mass of researchers working closely together is required for real breakthroughs in science. Similarly, chance interactions between researchers (of the same or different fields), which can result from colocation, have been thought to be beneficial in sparking new ideas. However, with modern technology and tools such as Skype and Twitter increasingly being used by scientists to communicate, interact and share with colleagues internationally, the importance of a critical mass working together is starting to be questioned. There may no longer be the need to build up a critical mass of researchers in one location or even one country.

This study has taken these caveats into account when analysing the findings of the research and has drawn on the expertise of RAND and the expert panel regarding changes in the relevant fields over time, as well as the emerging findings of the econometric analysis. The study has also explored these issues within the case studies themselves, where feasible.

An additional caveat that is more widely applicable to case study research is the generalisability of findings. With such a limited sample, it is not possible to generalise the lessons learnt from this set of case studies to wider research, neither within the United Kingdom nor internationally. However, it does allow for the illustration of some examples of the ways in which research funding and performance can be connected, and in particular, some of the complications and contextual factors involved with trying to understand these relationships. The case studies add some subtleties that allow us to understand and caveat the quantitative analysis appropriately. The cross-cutting analysis presented should not be seen as an attempt to generalise the results to research more widely. Rather, it is intended to illustrate some examples of the issues and complexities in understanding the relationship between funding and performance.

Figure 7: Steps to conduct case studies



3. Econometric analysis

3.1. Introduction

Countries differ substantially in the levels of funding available for research and subsequently the performance of research. In 2013, the latest year for which complete data are available, the share of GDP invested in research was over 4% in Israel and South Korea and 1.6% in the United Kingdom, while in developing countries it has generally been much lower. Substantial variation in research performance is also visible between countries. Through a cross-country study the relationship between research spending and performance at the macro level can be assessed. The econometric part of this study explores three major themes that will be discussed in turn. First, the relationship between levels of research funding and research performance across the 38 countries in the dataset will be assessed and the time-lags involved in this relationship will be explored. Second, the relationship between research spending and performance will be analysed, with disaggregated data for the United Kingdom. Due to the limited number of observations, the regression of the cross-country analysis cannot be repeated. Third, for a selection of countries with large research outputs, efforts are made to assess the efficiency of the production of (high quality) research.

3.2. The relationship between research spending and performance

The main topic of interest in the first part of the study is the relationship between research spending and research performance. While the link between spending and performance is in itself of interest, an important aspect of the relationship is time-lags. It is unlikely that change in funding will immediately result in change in performance, and it can be assumed that a time-lag will exist. Exactly how long the time-lag is, however, is not clear, and only a few studies have empirically assessed the length of time-lags.

Crespi and Geuna estimate the time-lag to be around five to six years, however, they argue that there is not a simple linear relationship between inputs and outputs[51]: 'The lag between investment and the research output is considerable and the impact first grows very slowly, peaks, and then drops quite

[51] Crespi and Geuna, 'An Empirical Study of Scientific Production'.

quickly. These characteristics could explain why it is frequently difficult to link research inputs and outputs.'

Using a more bottom-up approach, Boyack and Jordan link grant numbers to publications acknowledging the grant number and find that for National Institutes of Health (NIH) grants, the median time-lag is three years.[52] Acosta et al. find significant time-lags at three and five years, depending on the level of development of a region.[53]

This study follows the existing literature and uses HERD as the input variable. The total number of publications, the number of publications in the top one per cent of publications (Top 1% publications), the number of PhD graduates and the FWCI are used as output variables. Country differences are accounted for using the country fixed effects, as outlined in Chapter 2. The results from the analysis show that a significant relationship exists between changes in spending and changes in performance, meaning that statistically significant correlations can be established in the time-lag analysis presented below between the two variables, taking country factors into account. This implies that changes in spending are correlated with changes in performance, and thus that a substantial increase or decrease in spending will have an effect on the performance as measured in publications. As this outcome is to be expected, this study has focused most of its attention on the identification of time-lags between spending and performance.

To determine the lag length between spending and performance, the study applies a polynomial distributed lag model. It starts by using a lag of eight years and proceeds by reducing the total lag by one year until eventually, after eight steps, there is a zero year time-lag. In each reduction, the study evaluates the information lost as a result of the omission of one additional year of lag and the information gained from more degrees of freedom in the estimation. The first results are shown in Table 3 (publications) and Table 4 (Top 1%).

Both tables show the lag structure for each of the estimated models, which are interpreted in two steps. First, the overall fit of the models is assessed with different years of lag by examining the AIC and the SBIC.[54] AIC and SBIC information criteria suggest a four-year lag structure between research spending and publications or Top 1% publications (columns in **bold**). The columns for the four-year lag show the weights of each year on the outcome of interest for the four-year lag model. The model with four-year lags therefore provides the overall best fit. Second, within the four-year lag model, the study can examine the coefficients for each lag-year, meaning that each year that still has its own coefficient that can be statistically significant. The results for the total number of publications suggest that the impact of the first

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[52] K. Boyack and P. Jordan, 'Metrics Associated with NIH Funding: A High-Level View', *Journal of the American Medical Informatics Association* 18, no. 4 (2011): 423–31.

[53] M. Acosta et al., 'Regional Scientific Production and Specialization in Europe: The Role of HERD', *European Planning Studies* 22, no. 5 (2014): 949–74.

[54] The AIC and SBIC are goodness of fit measures of the same type as the well-known R-square metric. The main information exploited in both measures is the sum of squared residuals, of which the goal is to make as small as possible to present the model that fits the data 'best'. Hence, in applying these two criteria, we want to minimise the criteria and seek to choose the model specification with the smallest AIC or SBIC value.

year is very low and gradually increases to its highest in year one. It then decreases and is lower in years three and four than in years one and two. It is important to note that only years one, two and four are statistically significant.

The relationship between HERD and Top 1% publications shows a slightly different picture: the effect is higher in year one than in year two and is highest in year four. However, it is worth noting that only the impact in year four is statistically significant.

Overall, the four-year lag models provide the best fit, with statistically significant coefficients ranging from two to four years. Taken together, the study interprets the findings as suggesting that the average lag will be between two and four years. This appears consistent with some of the literature referred to earlier, and confirms the assumption that it takes time for changes in performance to become visible.

Table 3: Unrestricted Polynomial Distributed Lag (PDL) - Fixed Effects: Publications - HERD

Lag	8	7	6	5	4	3	2	1	0
herd	0.0233	0.0191	-0.0057	0.0068	**0.0114**	0.0190	-0.0012	0.0203	0.4517***
	(0.067)	(0.066)	(0.069)	(0.069)	**(0.069)**	(0.069)	(0.066)	(0.099)	(0.047)
L.herd	0.1358**	0.1298**	0.1560**	0.1515**	**0.1489****	0.1435**	0.1723***	0.4022***	
	(0.065)	(0.062)	(0.068)	(0.067)	**(0.067)**	(0.064)	(0.054)	(0.074)	
L2.herd	0.1501*	0.1599**	0.1635**	0.1586**	**0.1570****	0.1674**	0.2783***		
	(0.078)	(0.078)	(0.079)	(0.076)	**(0.078)**	(0.076)	(0.056)		
L3.herd	0.0772	0.0769	0.0650	0.0644	**0.0678**	0.1456***			
	(0.052)	(0.052)	(0.051)	(0.051)	**(0.051)**	(0.047)			
L4.herd	0.0949*	0.0925*	0.0809	0.0859	**0.1042****				
	(0.050)	(0.048)	(0.052)	(0.055)	**(0.047)**				
L5.herd	-0.0105	-0.0145	-0.0072	0.0277					
	(0.065)	(0.060)	(0.066)	(0.052)					
L6.herd	-0.0293	-0.0263	0.0546						
	(0.067)	(0.068)	(0.063)						
L7.herd	0.0915	0.1120**							
	(0.060)	(0.050)							
L8.herd	0.0297								
	(0.051)								
N	341	341	341	341	341	341	341	341	341
R-squared	0.9977	0.9977	0.9977	0.9977	0.9977	0.9976	0.9975	0.9970	0.9963
AIC	-1505	-1511	-1508	-1512	-1519	-1516	-1506	-1455	-1387
SBIC	-1553	-1558	-1554	-1557	-1563	-1559	-1548	-1496	-1427

Robust standard errors in parentheses;*** p<0.01, ** p<0.05, * p<0.10

NOTE: In each lag model the study controls for the number of researchers in a given country, GDP per capita, and a set of time and country fixed effects.

Table 4: Unrestricted Polynomial Distributed Lag (PDL) - Fixed Effects: Top 1% - HERD

Lag	8	7	6	5	4	3	2	1	0
herd	0.0770	0.0734	-0.0039	0.0178	**0.0107**	0.0479	-0.0162	-0.0165	0.5074***
	(0.222)	(0.224)	(0.217)	(0.218)	**(0.212)**	(0.236)	(0.277)	(0.285)	(0.137)
L.herd	0.3547	0.3495	0.4310	0.4232	**0.4271**	0.4006	0.4920	0.4885**	
	(0.273)	(0.271)	(0.290)	(0.298)	**(0.298)**	(0.280)	(0.340)	(0.211)	
L2.herd	-0.4205*	-0.4120*	-0.4009	-0.4093	**-0.4068**	-0.3557	-0.0043		
	(0.242)	(0.234)	(0.255)	(0.259)	**(0.259)**	(0.259)	(0.240)		
L3.herd	0.1247	0.1245	0.0877	0.0866	**0.0813**	0.4615***			
	(0.217)	(0.217)	(0.247)	(0.249)	**(0.266)**	(0.151)			
L4.herd	0.5660	0.5640	0.5281	0.5367	**0.5087***				
	(0.345)	(0.345)	(0.389)	(0.395)	**(0.294)**				
L5.herd	-0.1219	-0.1255	-0.1026	-0.0422					
	(0.216)	(0.217)	(0.248)	(0.205)					
L6.herd	-0.1597	-0.1571	0.0944						
	(0.160)	(0.164)	(0.148)						
L7.herd	0.3304	0.3481*							
	(0.226)	(0.202)							
L8.herd	0.0257								
	(0.120)								
N	341	341	341	341	341	341	341	341	341
R-squared	0.9896	0.9896	0.9891	0.9890	0.9890	0.9878	0.9867	0.9867	0.9859
AIC	-907.9	-914.7	-905	-910.7	-917.3	-887.5	-867.2	-874	-859.1
SBIC	-955.9	-961.7	-951	-955.7	-961.3	-930.5	-909.2	-915	-899.1

Robust standard errors in parentheses;*** p<0.01, ** p<0.05, * p<0.10

NOTE: In each lag model the study controls for the number of researchers in a given country, GDP per capita, and a set of time and country fixed effects.

The same analysis was performed for the remaining two output variables: number of PhD graduates and the FWCI. Results for PhD graduates are shown in Table 5 and suggest a six-year lag, which is longer than the lag found for publications. The output variable measures the number of graduates that complete their PhD. As PhDs take several years to complete, it is not surprising that there is a substantial lag between changes in funding and changing in the number of PhDs being delivered.

Table 6 shows the results for the relationship between HERD and the FWCI. Surprisingly, the lag structure here is minimal, but this may be due to the whole-counting method by which the FWCI data has been established. Through whole counting the number of citations effectively gets inflated,[55] and in the dataset the FWCI for nearly all countries increases over time. While it is beyond the scope of the current analysis, this inflation may make it more difficult to detect the exact lag, and thus the results of the FWCI are less reliable than for the other three output variables. The rest of this study's analysis will therefore not place much emphasis on this lag.

[55] For more information see: Waltman et al., 'The Leiden Ranking 2011/2012'.

Table 5: Unrestricted Polynomial Distributed Lag (PDL) - Fixed Effects: PhD Graduates - HERD

Lag	8	7	6	5	4	3	2	1	0
herd	0.0259	0.0202	**0.0192**	0.0005	0.1020	0.1464	0.1653	0.1300	-0.1364
	(0.175)	(0.174)	**(0.174)**	(0.173)	(0.171)	(0.174)	(0.178)	(0.186)	(0.152)
L.herd	-0.6969***	-0.7007***	**-0.6997*****	-0.6079**	-0.6550***	-0.6685**	-0.7218***	-0.3395	
	(0.257)	(0.249)	**(0.248)**	(0.251)	(0.250)	(0.265)	(0.272)	(0.238)	
L2.herd	0.3699	0.3815	**0.3909**	0.3218	0.2560	0.1838	0.4268*		
	(0.279)	(0.284)	**(0.274)**	(0.274)	(0.273)	(0.289)	(0.250)		
L3.herd	-0.2131	-0.1994	**-0.2086**	-0.2286	-0.2925	0.2801			
	(0.257)	(0.252)	**(0.250)**	(0.254)	(0.265)	(0.192)			
L4.herd	0.1629	0.1567	**0.1543**	0.1005	0.6779***				
	(0.275)	(0.274)	**(0.275)**	(0.275)	(0.202)				
L5.herd	0.3037	0.3024	**0.2944**	0.6784***					
	(0.315)	(0.312)	**(0.302)**	(0.213)					
L6.herd	0.3946	0.3758	**0.4326****						
	(0.336)	(0.331)	**(0.216)**						
L7.herd	-0.0206	0.0679							
	(0.254)	(0.207)							
L8.herd	0.1055								
	(0.168)								
Observations	297	297	**297**	297	297	297	297	297	297
R-squared	0.9896	0.9895	**0.9895**	0.9892	0.9882	0.9872	0.9871	0.9867	0.9865
AIC	-792.9	-798.8	**-805.2**	-802	-783.9	-767.1	-770	-768.7	-771.2
SBIC	-838.9	-843.8	**-849.2**	-845	-825.9	-808.1	-810	-807.7	-809.2

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.10

NOTE: In each lag model the study controls for the number of researchers in a given country, GDP per capita, and a set of time and country fixed effects.

Table 6: Unrestricted Polynomial Distributed Lag (PDL) - Fixed Effects: Field Weighted Citation Index - HERD

Lag	8	7	6	5	4	3	2	1	0
herd	0.0729***	0.0743***	0.0822***	0.0774***	0.0817***	0.0847***	0.0816**	0.0817***	0.0636***
	(0.027)	(0.027)	(0.029)	(0.029)	(0.030)	(0.032)	(0.032)	(0.031)	(0.015)
L.herd	-0.0141	-0.0126	-0.0207	-0.0189	-0.0213	-0.0232	-0.0184	-0.0168	
	(0.023)	(0.023)	(0.028)	(0.029)	(0.029)	(0.032)	(0.031)	(0.026)	
L2.herd	-0.0174	-0.0199	-0.0210	-0.0191	-0.0206	-0.0169	0.0019		
	(0.029)	(0.031)	(0.033)	(0.033)	(0.034)	(0.034)	(0.026)		
L3.herd	-0.0103	-0.0103	-0.0067	-0.0064	-0.0033	0.0247			
	(0.029)	(0.029)	(0.030)	(0.029)	(0.030)	(0.023)			
L4.herd	0.0185	0.0191	0.0227	0.0207	0.0375**				
	(0.019)	(0.019)	(0.021)	(0.021)	(0.018)				
L5.herd	0.0407*	0.0418*	0.0395*	0.0255					
	(0.021)	(0.022)	(0.022)	(0.018)					
L6.herd	0.0038	0.0031	-0.0218						
	(0.025)	(0.025)	(0.020)						
L7.herd	-0.0291	-0.0345**							
	(0.020)	(0.016)							
L8.herd	-0.0079								
	(0.018)								
Observations	341	341	341	341	341	341	341	341	341
R-squared	0.9921	0.9921	0.9919	0.9919	0.9918	0.9916	0.9915	0.9915	0.9915
AIC	-2150	-2157	-2157	-2161	-2165	-2164	-2167	-2174	-2179
SBIC	-2199	-2205	-2204	-2207	-2210	-2208	-2210	-2216	-2220

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.10

NOTE: In each lag model the study controls for the number of researchers in a given country, GDP per capita, and a set of time and country fixed effects.

3.2.1. Results for GERD

HERD is often used in literature analysing research spending and research performance as most measurable outputs (e.g. publications) will have been produced by higher education institutions that are funded through HERD.[56] However, not all outputs measured in the bibliometrics will have resulted from HERD spending, some will result from other spending sources captured, such as BERD. To check the results, this study performed the same time-lag analysis for GERD in order to be inclusive in terms of sources of research funding. The results are included in Appendix A and show that the best fitting model time-lag for Top 1% publications remains the four-year lag, with a significant coefficient in year four. The best fitting model for total publications, however, is a three-year lag model, with a significant coefficient in year three. Although slightly different from the HERD model, the findings substantiate the HERD findings of three to four year time-lags.

3.3. A look at the United Kingdom

The aim of the UK analysis is to understand differences between research areas at the national level. For this, disaggregate data are required for both spending and performance. Disaggregated spending data are based on an analysis of UK Funding Bodies and Research Council UK data, as outlined in Chapter 2. The spending categories identified are then matched with BIS categories in the bibliometrics database to allow for a disaggregated analysis at the UK level. Table 7 indicates the different spending areas, the matched BIS categories and the funders. The analysis for the United Kingdom is more limited in scope than the cross-country analysis as disaggregated funding data are not available for all years. It is therefore not possible to repeat the cross-country regression analysis at the UK level.

Table 7: Disaggregated spending and performance areas

Spending category	BIS categories	Funders
Clinical, health and biomedical sciences	1. Clinical sciences and 2. Health and medical sciences	NHS and MRC and FC
Biological sciences	3. Biological sciences	BBSRC and FC
Environmental sciences	4. Environmental sciences	NERC and FC
Mathematics, physical sciences and engineering	5. Mathematics, 6. Physical sciences and 7. Engineering	EPSRC, STFC, PPARC and FC
Social science and business	8. Social sciences and 9. Business	ESRC and FC
Humanities	10. Humanities	AHRC and FC

Note: AHRC = Arts and Humanities Research Council, BBSRC = Biotechnology and Biological Sciences Research Council, EPSRC = Engineering and Physical Sciences Research Council, ESRC = Economic and Social Research Council, FC = Funding Council, MRC = Medical Research Council, NERC = Natural Environment Research Council, NHS = National Health Service, PPARC = Particle Physics and Astronomy Research Council, STFC = Science and Technology Facilities Council

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[56] See for example: Auranen and Nieminen, 'University Research Funding and Publication performance—An International Comparison'; Crespi and Geuna, 'An Empirical Study of Scientific Production'; Leydesdorff and Wagner, 'Macro-Level Indicators of the Relations between Research Funding and Research Output'.

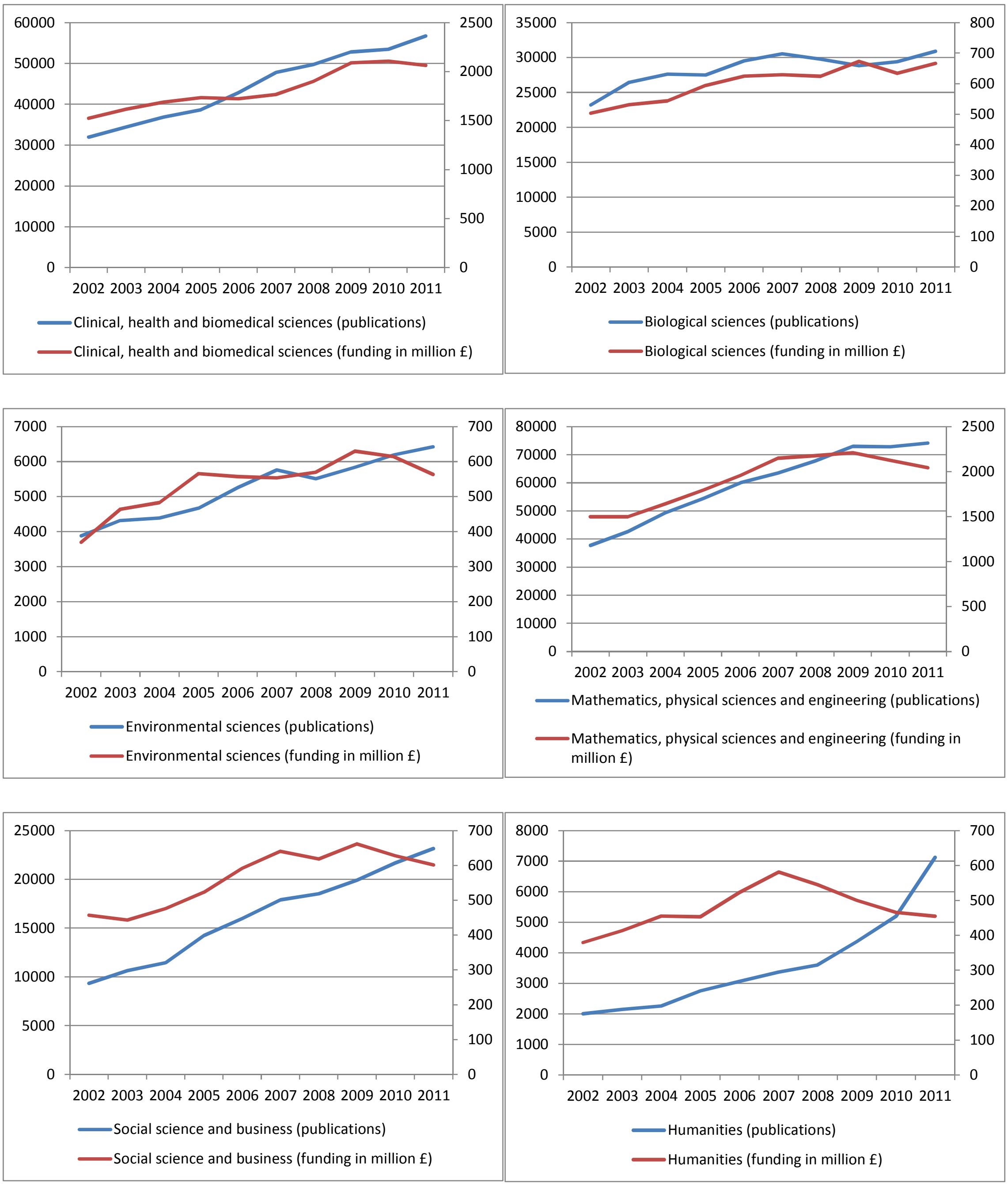
On the basis of the spending categories above, this study can provide broad overviews of the trends in spending and the total number of publications (Figure 8); and of spending and the number of Top 1% publications (Figure 9). For most categories, the relationship is straightforward: with increases in spending over time, the number of publications, both total volume and Top 1%, increase. In cases where the distance between the lines change, the ratio between spending and publications changes, however these are generally small changes and do not take time-lags into account. Overall, the results replicate the findings from the cross-country analysis in section 3.2 and, with the exception of the humanities, do not show substantial category differences.

The graphs for the humanities show a substantial increase in the number of publications over time. Part of this may be due to the relatively recent formation of the Arts and Humanities Research Council (AHRC), which has led to funding increases for the humanities over a ten-year period (2001-2011). However, a growing inclusion of arts and humanities journals in bibliometric databases is also likely to have substantially contributed to the growth of publications.[57] This means that the actual number of publications is not likely have increased as much as the graph implies. Instead, an increasing number of articles are included in the bibliometric database.[58]

[57] Elsevier, 'Research Trends Issue 32' (Elsevier, 2013).

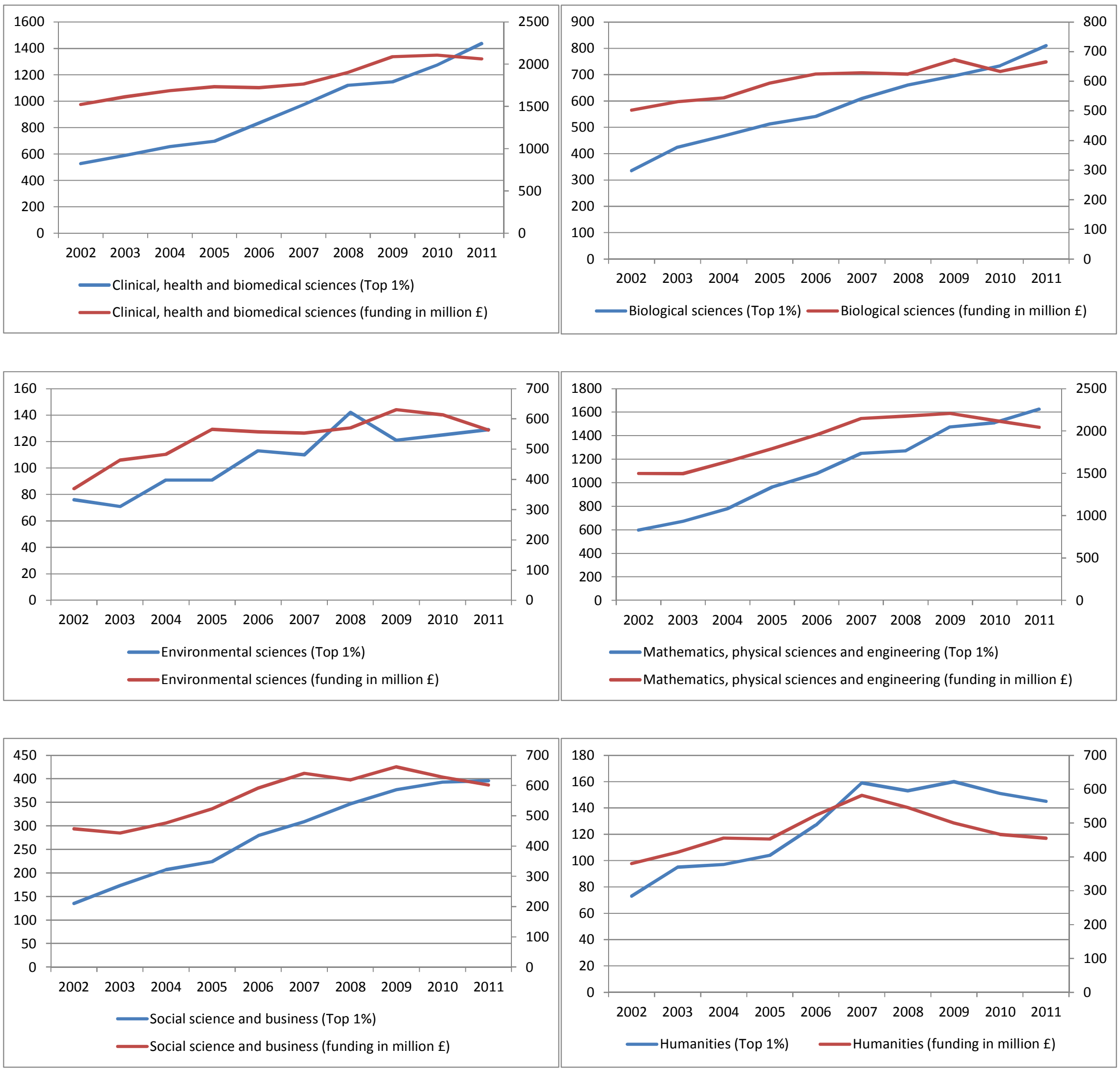
[58] We thank the Arts and Humanities Research Council for this observation.

Figure 8: Spending and total publications by category, United Kingdom (2001-2011)



NOTE: Total publications on the left axis; spending on the right axis in million £ (inflation adjusted)

Figure 9: Spending and Top 1% publications, United Kingdom (2001-2011)



NOTE: Top 1% publications on the left axis; spending on the right axis in million £ (inflation adjusted)

3.4. Productivity

The findings from the regression analysis in section 3.2 indicate that increased spending on research will increase research performance. However, as shown below, differences remain between countries in the level of spending that is required to achieve similar levels of performance. In short, some countries are more productive or efficient than others. Efficiency or productivity measures of scientific output are not new.[59] If productivity is defined as the output generated by the inputs, it is possible to estimate which countries have higher productivity levels than others by using the input and output measures defined in Chapter 2. One of the estimates of productivity that uses this approach is the assessment of the *Scientific Impact of Nations* by King.[60] In recent years the analysis of productivity has been further developed to understand the different drivers of productivity.[61] As the focus of this study is on the relationship between research spending and performance, the more straightforward approach to productivity assessment set out by King is followed and expanded upon by also examining productivity with a four year time-lag.

For productivity this study conducts two separate analyses, one for the total number of publications and one for the Top 1%, and for both without a time-lag and with a four year time-lag. Findings of a subset of countries that produce a large share of the world's scientific output are reported, namely Canada, China, France, Germany, Italy, Japan, the United States and the United Kingdom.

Two main conclusions can be drawn from the results shown in Figures 10 and 11. First, China is remarkably productive in the production of publications. Per unit of HERD China produces far more publications than any other selected country, and this logically holds for both the analysis with and without time-lags. The caveat to be made here, however, concerns the average number of citations of the papers. While China produces a large number of papers, the overall level of citations of these papers is below the world average of one, as Table 8 shows.

Table 8: FWCI for total publications from China (1996-2012)

1996	1997	1998	1999	2000	2001	2002	2003	2004
0.465	0.483	0.5	0.527	0.561	0.602	0.65	0.665	0.662
2005	2006	2007	2008	2009	2010	2011	2012	
0.653	0.661	0.676	0.695	0.712	0.733	0.748	0.764	

Source: Scopus, Elsevier

59 King, 'The Scientific Impact of Nations'; Leydesdorff and Wagner, 'Macro-Level Indicators of the Relations between Research Funding and Research Output'; May, 'The Scientific Wealth of Nations'; Wendt et al., 'Challenges in Cross-National Comparisons of R&D Expenditure and Publication Output'.

60 King, 'The Scientific Impact of Nations'.

61 C. Chen, J. Hu, and C. Yang, 'Produce Patents or Journal Articles? A Cross-Country Comparison of R&D Productivity Change', *Scientometrics* 94, no. 3 (2013): 833–49; W. Hung, L. Lee, and M. Tsai, 'An International Comparison of Relative Contributions to Academic Productivity', *Scientometrics* 81, no. 3 (2009): 703–18; E. Wang and W. Huang, 'Relative Efficiency of R&D Activities: A Cross-Country Study Accounting for Environmental Factors in the DEA Approach', *Research Policy* 36, no. 2 (2007): 260–73.

Figure 10: Publications by HERD, selected countries (1996-2012)

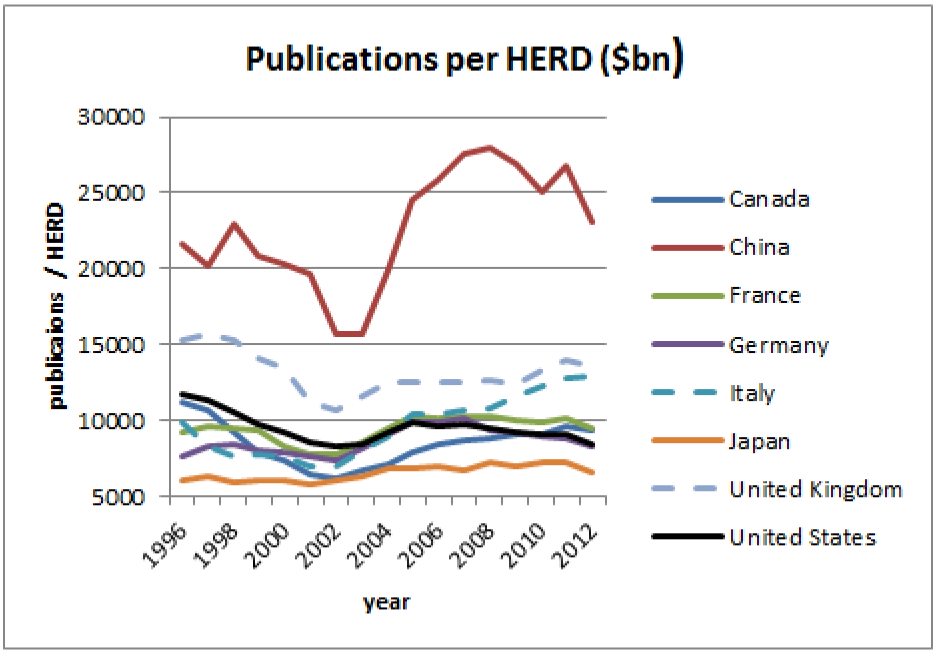
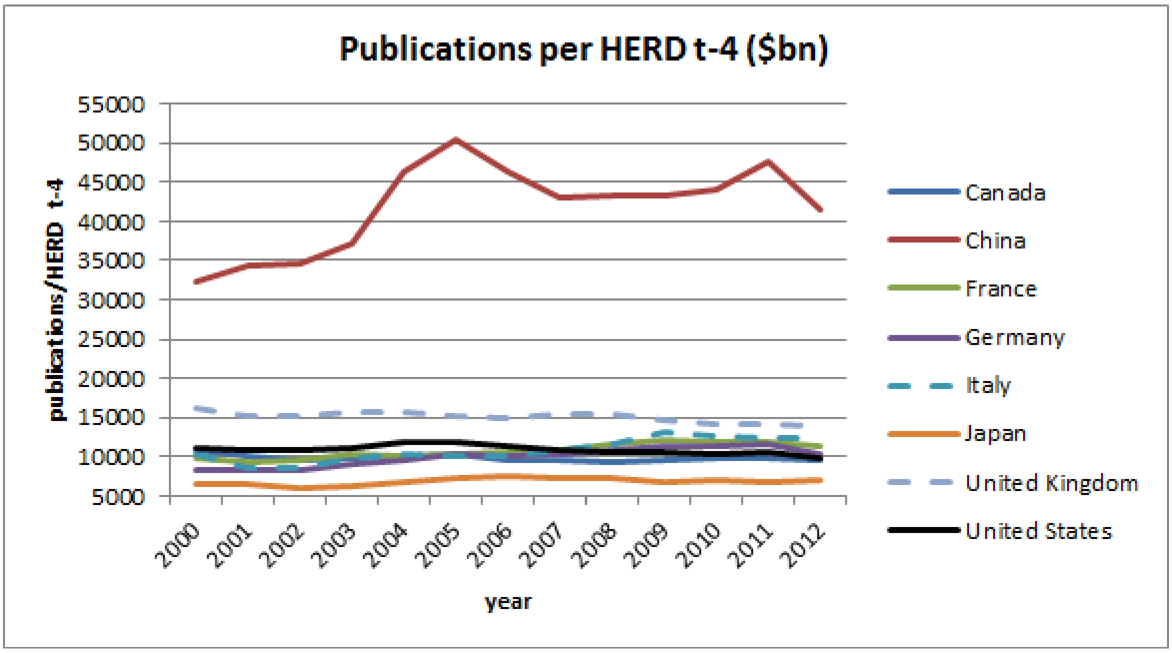


Figure 11: Publications by HERD t-4, selected countries (2000-2012)



The second conclusion from the results shown in Figures 10 and 11 is that the United Kingdom remains the most productive country in the production of Top 1% publications (Figure 12 and Figure 13. Per unit of HERD, the United Kingdom produces the most Top 1% publications, which means that it is most efficient in the production of the world's most cited publications. The sheer volume of publications from China, however, means that the country is quickly rising up the ranks of producers of the Top 1% publications: from number seven to number two when the time-lags are taken into account. It could therefore be assumed that in the future China may overtake the United Kingdom as the most productive country in producing Top 1% publications.

Figure 12: Top 1% by HERD, selected countries (1996-2012)

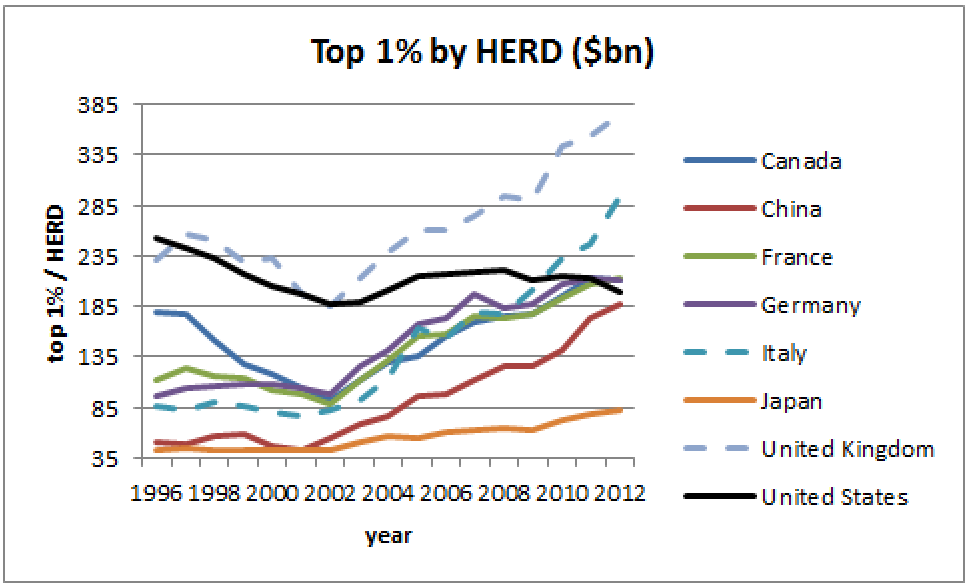
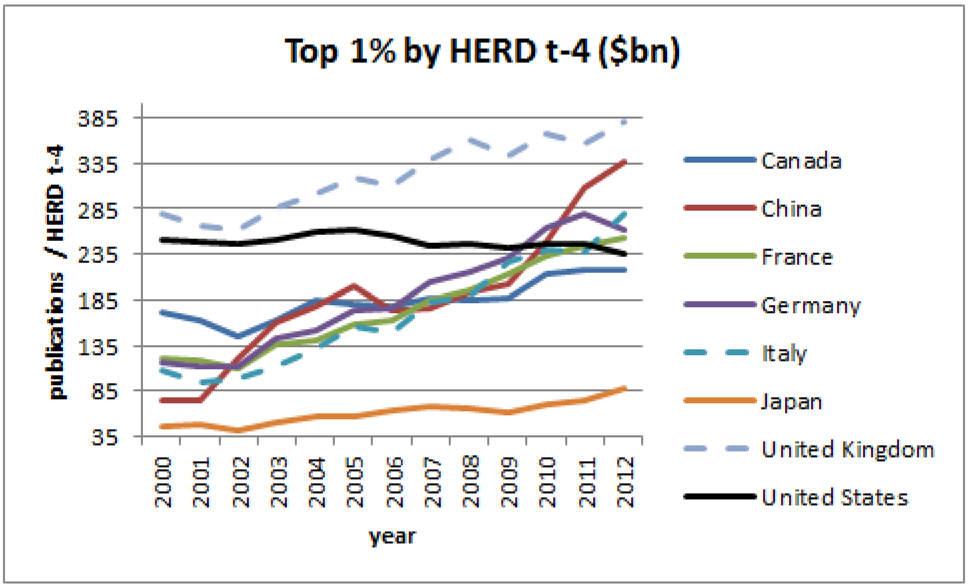


Figure 13: Top 1% by HERD t-4, selected countries (2000-2012)



Non-cited papers

An important caveat relating to calculations of productivity is that in contrast to the Top 1%, measures of productivity on the total number of publications do not take the quality of the papers into account.

Among the total number of publications, many papers are uncited, and therefore simply looking at the quantity of publications may not say much about research quality in a country. The data show that the share of uncited papers is higher in China than in the United Kingdom or the United States, but in all countries the share of uncited papers is increasing. For recent years, the share of uncited papers is necessarily higher as it takes time for citations to accrue. However, despite this lag, the increasing share of uncited papers shows that while the productivity and volume of academic output may increase, the papers may not necessary be cited or used by others.

Table 9: Percentage of uncited publications

Comparator	1996	2000	2005	2010	2012
World	28.6	26.0	30.4	40.0	70.0
China	44.7	34.4	35.4	50.5	77.0
United Kingdom	14.7	13.0	16.3	25.1	56.8
United States	17.7	13.7	20.0	27.6	59.0

Source: Scopus, Elsevier

4. Case Studies: Cross-cutting themes

The individual case studies each provide a rich account of changes in academic fields with detailed information to verify, illustrate and challenge initial claims of cliff-edge and take-off. Cross-cutting the five case studies are five more general themes, identified through internal team meetings and a workshop with the project advisors, that provide more general substance to the notions of cliff-edge and take-off, and to the underlying relationship between research spending and research performance. These cross-cutting themes will be discussed in-depth in this chapter with continuous reference to the individual case studies. The five themes provide different insights into the concepts of cliff-edge and take-off and complement the conclusions drawn from the econometrics in Chapter 5. Summary descriptions of the case studies are included in Appendix B.

Before analysing the five themes it is important to reiterate that the content of the case studies was based largely on information gathered through interviews. While the interviewees were carefully selected, the data still rest largely on their opinion, which adds an element of subjectivity that needs to be recognised. As mentioned in Chapter 2, however, the aim of the case studies was not to understand in-depth the different fields analysed, but rather to explore whether the conceptual framework of cliff-edge and take-off is useful for analysing the relationship between changes in research spending and performance.

4.1. Theme 1: Cliff-edge and take-off depend on perspective

The classification of an episode as cliff-edge or take-off is strongly dependent on individual or stakeholder perspectives. In several cases it was found that what was perceived as a cliff-edge by some stakeholders, generally academia, was not perceived as such by other stakeholders, such as policy makers. This has implications for the conceptual value of cliff-edge and take-off, which will be further explored later on. The case studies show different judgements of a similar change or episode are not simply the result of differences of opinion, but often stem from different perspectives on what a high-quality research field looks like and what kind of information it should produce. From the perspective of academia, for example, only the most sophisticated methodologies and data may constitute high-quality research; while from the perspective of the policy maker, any field that can produce robust and useable data constitutes high-quality research, even if it does not involve the most sophisticated methodologies. These differences result in different judgments as to whether a change is a cliff-edge or take-off.

In air quality, for example, the closure of publicly funded laboratories in the early 1990s seemed to mark a shift from experimental work to modelling work and was perceived by academia as a loss and cliff-edge.

However, others, among them policy makers, noted that information gathered through both approaches could be used to inform policy decisions, and as such, there had not been a clear cliff-edge.

Perspective is not limited to a one-dimensional opposition of policy-makers versus academics. Other case studies show that within academia, for example, judgments can differ about the development of a field. In the case of semiconductors, the perspective of former academics, who deemed semiconductor research to be a cliff-edge, differed substantially from those still active in the field, who pointed to changes, rather than cliff-edges, in the field.

4.2. Theme 2: Declining versus evolving fields

The evolution of a research field can lead to different interpretations, as the case of semiconductors mentioned in theme one appears to show. To some, a field may evolve, to others it's in decline. Important in these judgements is how the field is defined. A broad conception of a field may yield a different judgment than a narrow conception. While these judgements may be subjective, there are aspects to this theme that can be explored empirically to generate a more objective understanding of whether a field is in decline or evolving. First, changes to a field can be studied using bibliometrics. Second, the drivers of change can be explored, which may provide insights into the background of the different judgments.

Several case studies attempted to explore the evolution of fields using bibliometric data from Scopus.[62] With Scopus, a particular field can be searched for as a keyword (e.g. semiconductors) and then the related keywords that appear most frequently can be analysed. Given the large volume of publications, this exercise was most useful for semiconductors.

The results for semiconductors allowed for two broad conclusions. First, the volume of publications on semiconductors in the United Kingdom has remained relatively stable. If assuming that publication volumes can only be maintained if the research base is maintained, then it seems unlikely that the field has declined significantly. Second, the analysis of keywords that appear most frequently in combination with 'semiconductors' revealed possible changes in the field. As certain keywords become less frequent (e.g. names of materials, such as silicon or gallium) other keywords become more frequent (e.g. quantum wells, quantum dots). Combined with data gathered through interviews that suggested a shift in the field to work linked to developments in nanotechnology, this indicates that the field may be evolving rather than declining. However, a more thorough study of the field is required before any firm conclusions can be drawn.

A second way to empirically assess decline and evolution is to study possible drivers of change. For example, if certain research activities are discontinued because funding was withdrawn, this may signal a cliff-edge. However, if research activities are discontinued because scientists shift to new areas or new technologies, it may not be a cliff-edge, but simply a natural progression of science. The case study of air

[62] The general website from Scopus was used, as the Scopus dataset provided for this study and used in the econometric study did allow for this analysis.

quality is an example of a possible cliff-edge, as experimental work was no longer (substantially) funded; whereas NMR, and specifically the increased use of NMR in biomedicine (while not necessarily at the expense of other areas), may signal a shift in scientific focus. As with bibliometrics, there are various other drivers of change, and a full assessment of these, and how they relate to changing fields, is beyond the scope of the study.

4.3. Theme 3: The importance of the wider context

In any study of change, context is important, and the case studies reconfirm the importance of understanding the context in the assessment of cliff-edges and take-offs. The case of soil science shows that a policy need may have driven the changes in research funding and subsequent research performance, and the case of semiconductors points towards the importance of understanding changes in the global semiconductor industry. To view the changes in research fields in isolation could yield inaccurate judgements about their development.

Evidence from the case studies suggests that in some cases, changes that may be, at least in part, due to wider exogenous factors could be interpreted as changes in research performance driven by changes in funding and support.[63] The case of semiconductors is one example. Taking correlations at face value, and not fully understanding the subtleties around the various factors related to the wider context, may result in only partially true conclusions. This is important to consider not only when interpreting the econometric analysis conduct, but also when trying to understand and interpret comments made around funding and performance by interested parties.

4.4. Theme 4: Mechanisms linking changes in research spending and research performance

At the start of the study, mechanisms were identified as the processes through which spending decisions are transferred or translated into step-changes in research capacity and research excellence. These can vary from the (dis)investment in capital to the hiring/firing of academic staff. In the case studies, the mechanisms that may underlie an episode of cliff-edge or take-off were explicitly explored. Three areas that may serve as mechanisms are focused on: infrastructure, researchers, and the organisations of research and researchers.

Infrastructure is an intuitively straightforward mechanism. When funding for infrastructure in a field is reduced, a reduction in performance can be expected, and vice versa. However, such straightforward changes are rarely observed, with the possible exception of unique infrastructures. In most cases development is less straightforward, although it still provides insights.

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[63] It is generally difficult to establish cause and effect in these case studies, however. It might be that the funding changes are responding to these exogenous factors and driving changes in research focus. This does not seem to be the case in the example of semiconductors, but is a realistic scenario in other cases.

The first insight relates to a distinction between investment in the maintenance of infrastructure and investment in new infrastructure. While both are deemed necessary to maintain world-leading research, they fulfil different functions. Maintenance of existing infrastructure supports world-leading research, but importantly also supports the education of new researchers, which supports the maintenance of the research base. New, state-of-the-art infrastructure performs the slightly different function of allowing the exploration of new methodologies and new experiments that are not possible within existing infrastructure. As such, the mechanism through which funding changes translate into performance changes can differ depending on which type of infrastructure is or is not supported.

As well as maintenance and upgrade of existing infrastructure, there may also be significant ongoing costs with the operation of infrastructure. This is an issue that has been suggested as potentially problematic in relation to medium-sized facilities, such as NMR,[64] as well as large-scale facilities, such as ISIS and DIAMOND.[65] There may be a parallel to the issue of ongoing versus set up costs for cohort studies that is not observed directly in these case studies. This study noted that it took a dedicated team of researchers to maintain the cohorts as funding for ongoing data collection was not always easy to obtain.

The movements of researchers are logically related to the availability of infrastructure, and a decline in infrastructure will likely lead to a decrease of researchers in that field. As facilities for air quality research were shut down in the early 1990s (closure of Warren Spring Laboratory), researchers moved away from experimental research towards modelling (which requires less infrastructure investment). However, this link involves further complexities. First, not all infrastructure attracts the same kind of researcher. Through the case studies of NMR and cohort studies it appears that world-leading infrastructure and data (e.g. cohort studies) do attract world-leading researchers as they are mobile and will seek the best possible facilities. This link with world-leading researchers is not clear for the ‘underpinning’ research infrastructure, which, as mentioned above, performs slightly different functions. Second, the cohort study further showed that world-leading data can attract world-leading researchers in ways similar to infrastructure. Attracting and retaining researchers can therefore occur in multiple ways.

4.5. Theme 5: Early (warning) signs

Identifying the signs that a field is either approaching a cliff-edge or taking-off is not always straightforward. At the start of the case studies it was expected that cases of cliff-edge and take-off would not be as clear-cut as some of the statements serving as their rationale for inclusion would make it seem. The extent to which some cases were nuanced, however, was substantial.

Caution should be taken regarding the attribution of signals or signs from areas outside of research to the development of research. Signals from, for example, industry may not be reflective of developments in

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[64] Watts, A. (2012) Written evidence: Nuclear Magnetic Resonance – at a watershed. In: House of Lords, Science and Technology Select Committee: Scientific Infrastructure, Oral and Written Evidence

[65] House of Lords, Science and Technology Select Committee (2013) Scientific Infrastructure: 2nd Report of Session 2013–14

research. Even if the timelines match, such co-occurrence cannot directly be taken as evidence of a causal link. Each sign, therefore, needs to be examined in its own right as it is very likely that the reality is much more complex than initially anticipated. In the case studies, there is rarely a single driver of change, and usually a combination of factors determines the course of events. It can then depend on interpreting which factor is perceived as most important.

This study identified characteristics in more than one case study that were associated with cliff-edge or take-off. The first was the identification of a priority area for policy makers. This can indicate that there is interest in supporting research in a field and, where other factors are in place and there is capacity to take up that opportunity, could act as an early indicator for potential take-off. This was seen in the cases of soil science and air quality. While causal relations are not claimed by the case studies, soil science was identified as a priority by European Soil Thematic Strategy in 2006, which coincides with a subsequent growth of the field. By contrast, a policy-driven focus on climate change research in the early 1990s was seen by interviewees as playing a role in the decline in the related field of air quality through the displacement of research funding and researchers from air quality to climate change research.

The second characteristic was the relative numbers of senior staff in a field compared to PhDs. In soil science, a seemingly growing field, interviewees noted that there were a high number of PhD students, as PhDs are a focus of funding to bring new people into the field. By contrast in air quality, interviewees noted that senior staff were able to find funding to continue their established research, but they were finding it more difficult to get enough funding to additionally support junior staff.

Both of these characteristics have some level of face validity. However, to establish whether they are appropriate early warning signs of cliff-edge and/or take-off would require further investigation. What does seem to arise from the case studies, though, is that science is always evolving and may not be suitable for studying through relatively black and white concepts like cliff-edge and take-off. Some factors may accelerate change in time; however, it always seems to be embedded within a larger context of change and development.

4.6. Methodological observations: How to improve future case studies

As the case studies were exploratory in nature, some observations can be made on how they can be further improved in the future. First, it is important to specify the research question more clearly upfront and to understand what kind of information and data are needed from the case study to ensure that it is focused and targeted. While this may potentially make the case studies less broad, it need not compromise its exploratory nature. More focus can ensure that the data derived can be better used to answer specific policy questions.

Second, more targeted research questions can allow for a more thorough investigation of the path of change. When the research question is too broad the case study is unlikely to be focused on a specific episode of change, which makes it more difficult to identify exactly what happened and why. A more targeted research question would allow for a quicker identification of the episode of change and hence for a more thorough investigation of the path of change, the drivers and the outcomes.

Third, more thought could be given upfront to the level of analysis of the case studies and the trade-offs that exist between different levels of analysis. Case studies at a lower level of analysis that have a more clearly defined unit of analysis, such as a particular institution or research project, are more likely to provide accurate information on the path of change than case studies at a higher level of analysis, such as entire research fields. The latter, however, will generate data that can be generalised to a greater degree and is also likely to be of greater use from a systems perspective. For all case studies, it will be important to decide upfront, and in interaction with the framing of the research question, what the level of analysis will be as it will determine the kind of data that will be gathered.

4.7. Cliff-edge and take-off in the arts and humanities

There are several minimum requirements for the study of potential cliff-edges and take-offs in the arts and humanities. The first is that there are indicators of research quality that can be tracked over time. These indicators will depend on the type of research output produced, which is where the arts and humanities differ from other academic disciplines. The second requirement is that there are fields or research areas that can be tracked over time. For analytical purposes, some field delineation is necessary for the identification of either a cliff-edge or take-off. Both requirements will be considered in turn.

Indicators of research quality

The arts and humanities differs slightly from other academic disciplines as it tends to distinguish itself by the different type of research conducted and the nature of the outputs produced. As data from the 2013-2014 Impact Report of the AHRC show, outputs in the arts and humanities can take many different forms (see Table 10).

Table 10: Outputs reported by the AHRC

	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14
Journal articles	820	961	816	668	503	247
Books	1000	1158	945	492	475	132
Conference papers	478	500	376	321	280	218
Other publications	290	331	185	119	122	91
Creative	546	479	557	256	82	71
Electronic	543	568	440	267	185	96
Physical	14	13	36	30	30	14
IP and exploitation	4	1	0	2	0	38
Dissemination/communication activity	2749	3872	3286	1424	1316	904

Source: Arts and Humanities Research Council (2015)[66]

[66] Arts and Humanities Research Council, 'The Impact of AHRC Research 2013-2014' (London: AHRC, 2015).

The diversity of outputs implies that the quality indicators used in this report for other disciplines may not be relevant for all the outputs produced in the arts and humanities. In order to know if a cliff-edge or take-off has occurred it is necessary to consistently track indicators over time. This means that indicators will have to be found to track the (quality of) different outputs over time. Indicators for journal articles and conference papers may be similar to the ones used in other disciplines, such as number of publications and citations. Bibliometric coverage, however, differs substantially within the arts and humanities and the largest fields in terms of titles listed in Scopus are history, literature and literary theory, language and linguistics, and philosophy.[67] In these fields, the bibliometric indicators would likely be of more use than in others. For other outputs, different indicators will need to be established. Depending on the output, indicators to consider are:

- Collaborations: has the research been based on either national or international collaboration? This could be an indication of the recognition of research quality.
- Capacity building: has the research contributed to capacity building? The development of new (human) capacity can be an indication of research strength in a field.
- Applications/proposals: the number of applications or proposals in a field can be an indication of the available research capacity in that field.

As mentioned in the methodology, impact indicators are not detached from research quality and can shed light on the quality of research outputs. For example, attendance at events and the usage of electronic or physical outputs are statistics that can be used as indicators of quality. However, it can take time for such data to become available.

Research fields

To know whether or not a cliff-edge or take-off has taken place it is necessary to define fields and delineate one area of arts and humanities research from another. A starting point can be the classification used by the AHRC for successful awards. Table 11 shows the 20 most frequently used classifications that contain a number of 'classical' arts and humanities fields, such as media, history, archaeology and philosophy.

[67] W. Meester, 'Towards a Comprehensive Citation Index for the Arts & Humanities', *Research Trends* 32 (2013).

Table 11: AHRC numbers of successful awards

	2010	2011	2012	2013	2014
Top classification description	#of Apps	#of Apps	#of Apps	#of Apps	#of Apps
Media	14	11	17	13	11
History	55	49	102	71	54
Archaeology	21	17	17	26	9
Philosophy	30	21	33	19	14
Design	9	7	18	14	24
Theology, divinity & religion	12	6	10	8	4
Classics	7	5	9	7	3
Languages & literature	77	64	90	44	39
Cultural & museum studies	33	7	36	32	23
Law & legal studies	10	9	17	3	10
Music	23	16	27	9	15
Visual arts	34	24	29	25	13
Development studies	2	1	3	1	
Drama & theatre studies	15	14	11	14	9
Pol. sci. & internat. studies	2	5	3	2	2
Linguistics	2	7	9	4	6
Dance	2	1	3	1	1
Library & information studies	2	3	5	3	5
Sociology		1	3	9	9
Education		1	5	3	3

Source: data provided by the AHRC; 'Apps' refers to Applications

A second way to identify fields to observe over time is to focus on individual programmes or initiatives. In recent years, the AHRC has started a number of programmes and initiatives, such as Knowledge Exchange Hubs, which could potentially serve as a unit to track. They are likely to only serve as potential take-offs rather than as cliff-edges, as for a programme to be a potential cliff-edge it would need to have existed for some time. Young programmes that do not perform well would not have 'taken off' but are also not a cliff-edge.

The combination of a broader set of indicators with a delineation of fields can allow for similar case studies to be conducted in the arts and humanities. These case studies are likely to be more diverse than the case studies conducted in other disciplines, yet could similarly point to cliff-edges and take-offs. It may be possible to track changes in 'classic' humanities, such as history and philosophy, over a longer period of time as these subjects are well established.

5. Conclusions

This study draws two types of conclusions: one applies to the general relationship between research spending and research performance, and the other applies to the United Kingdom specifically.

5.1. The relationship between research spending and performance

The first empirically verified conclusion is that there exists a link between the change in research spending and research performance. This implies that countries that invest substantially in research are, over time, likely to increase their research performance. It can therefore be expected that countries that invest an above-average amount in research will move up the ladder of research performance. The data analysed in the cross-country study show that certain countries have invested substantially in research in recent years (e.g. China), which becomes visible on the performance side in the data from the case studies, for example, in the number of publications on semiconductors from China.

The second conclusion is that the effects are not immediate. It is known from the literature that the effects are lagged, however, by how many years is uncertain. Time-lags of three or six years have been assumed in the literature, however they have not always been based on empirical findings. The analysis in this study suggests that time-lags are likely to be around three to four years for publications, possibly dependent on the type of output (e.g. total publications or Top 1%), and around six years for PhD graduates.

The time-lags apply both in the case of investment and disinvestment. The findings suggest that investment today will take time to become visible, and, as the case of the humanities shows, may even lower the average of the field (e.g. FWCI) as it will be in development. Decreasing FWCI are therefore not necessarily indicators of cliff-edges. Disinvestment today will also take time to become visible. Work already ‘in the pipeline’ may still be finished despite declining budgets, which may give the appearance that a field stays healthy, yet decline will follow, albeit lagged. This is a risk emphasised by the case of NMR: while declines in performance may not be directly visible, a possible erosion of the research base due to underinvestment could show a decline in performance in future years.

The third conclusion from the cross-country analysis shows the comparatively limited funds in the United Kingdom, which leads to questions surrounding where to invest. This is a question that was not part of the study but that was discussed during the case studies. Interviewees indicated that having world-class facilities would probably attract world-class research, which is an argument in favour of investment in the world-class facilities top of the pyramid. However, interviewees also suggested that investment in the research base are essential for long-term success. The trade-off is not an easy one, but the case studies did reveal that sometimes funding for world-class facilities is easier to obtain than investment in the maintenance of the existing research base. This could have negative implications for the long-term development of the research base.

5.2. Observations on the United Kingdom

The data confirm that the United Kingdom remains a productive country in producing Top 1% and continues to 'punch above its weight'. However, these headline figures do not show the variations between disciplines, even though substantial differences exist in how they develop. This study is limited in how it can disaggregate the data for the United Kingdom, however, the case of the humanities shows that interesting developments occur beneath the surface of headline figures (section 3.3). Such changes and developing fields are further substantiated by the case studies, where the idea of an 'evolving' field arose in multiple cases. To understand research performance in the United Kingdom, it therefore remains important to disaggregate the data and understand differences between fields.

The case studies show that opinions about the development of a field cannot be taken at face value. Fields may evolve and developments in other sectors, like industry, may not be reflective of the development of research. The limitations of the cross-country analysis and headline figures are illustrated by the greater level of detail gathered through the case studies. Data can complement each other, as in the case of semiconductors, where quantitative data on publications, together with qualitative data from the interviews, help to understand the development of a field.

On the basis of the percentage of GDP invested in research, the United Kingdom is no longer the top-investor in comparison to other research-intensive countries, such as Japan (section 3.1). While the United Kingdom still draws on a legacy of high quality research, the risk noted by Allas[68] is that that it is falling behind in terms of spending. The implications of this are likely to be lagged, as this study's analysis shows. Changes in performance are not immediate and will generally take three to four years to become visible. The data on spending today can therefore not directly be compared to the data on performance today, as part of the performance today is the result of spending three to four years ago.

The analysis of the bibliometric data, together with the case studies, cautions against the use of simplistic 'warning signs', such as an individual expert's opinion, for the development of scientific fields. The case of the humanities shows that simply using an indicator such as the FWCI for a field may not convey the entire picture, and may even obscure wider development. Additional sources will always be needed to fully understand the development. Different types of evidence are useful and should be collected and analysed. The data are strongest, however, when used in combination to complement each other and produce a holistic view of the relationship between research spending and performance.

[68] Allas, 'Insights from International Benchmarking of the UK Science and Innovation System'.

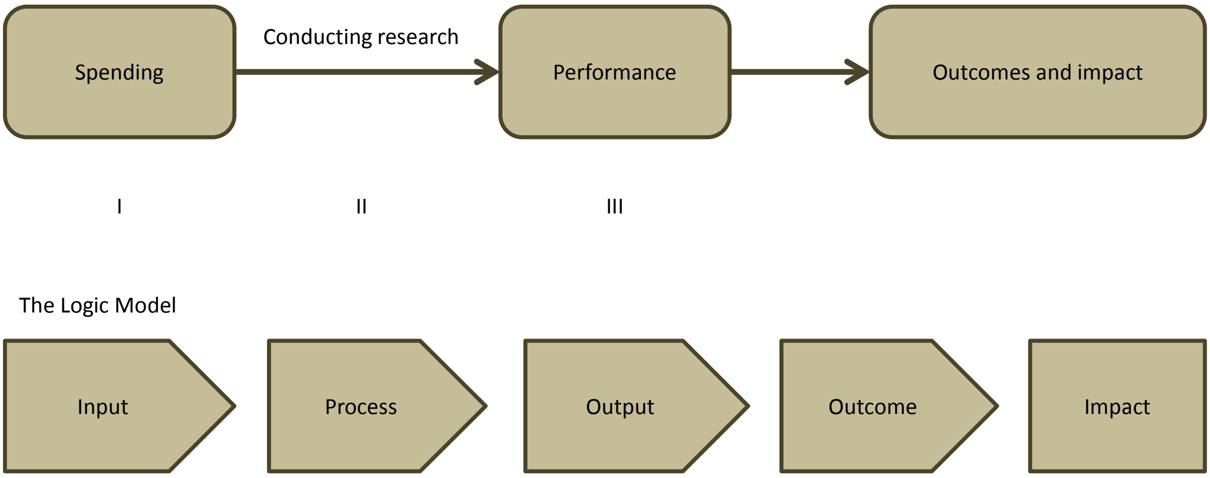
6. Scope for future research

The current available data have allowed for an interesting analysis of publication and citations patterns and their correlation with changes in research funding. However, as noted throughout the preceding chapters, a number of limitations and unanswered questions remain. This final chapter offers a forward looking perspective on the feasibility to answer or potentially investigate several aspects of research funding that have been identified as being relevant to policy. The areas have been suggested by BIS and reflect some of the strategic policy issues faced by policy makers. The three areas relate to different aspects of research funding:

1. Competitive versus non-competitive funding: there is a question about the potential of competitive research funding to influence academic activity and potentially affect publication and citation patterns.
2. Basic versus applied funding: the categories of basic and applied science are frequently used and there are questions around a potentially "optimal balance" between the two categories.
3. Capital versus resource funding: the United Kingdom differentiates science funding into capital and resource, questions similar to basic and applied science funding exist over an "optimal balance".

These questions aim to further disaggregate the link between research spending and research performance, which in this study were still two largely aggregated entities. A further disaggregation of the elements within the relationship may lead to a more precise understanding and may also point to differences between fields. Revisiting the simple logic model introduced in Chapter 2 shows how these areas can help disaggregate a number of the elements of the model:

Figure 14: The logic model from spending to impact



For each of the three areas relevant to policy there are a number of factors to consider from the perspective of future research. First, it is interesting to understand what is currently known about these areas. The current data available do not allow for disaggregated analyses and as a complete investigation is outside the scope of this chapter, a scan of the literature will be relied upon instead. Second, this study assesses what data are currently available on these three areas, both in international comparative datasets (as used in this study) and in a selection of case study countries. Experts in national research statistics in a number of selected countries were interviewed to assess what data would be available in their country. On the basis of this scoping exercise, it is possible to get a sense of the type of data that could potentially be collected on these areas from different countries. The following countries were reviewed:

Table 12: Case study countries

Country	Interview?	Interviewee institution
Australia	Yes	Department of Industry and Science
France	Yes	Ministry of National Education, Higher Education and Research
Canada	Yes	Statistics Canada
Italy	No – but email communication	National Institute of Statistics Italy
Spain	Yes	National Statistics Institute
Germany	No	N/A

The interviews were complemented with reviews of national statistics on research spending. The reviews and the interviews provide an overview of the currently available data and the current data gaps. Through the current research identified in the literature and the assessment of data availability it is possible to ask whether or not the areas identified are viable routes for future research.

Before these areas are addressed it is useful to flag several general caveats, some of which repeat caveats mentioned earlier in this report. First, the current data only allow for the assessment of 'outputs' as specified in the simple logic model above, but not any wider social or economic impact. However, the 'right' or 'optimal' balance of funding, if such balances exist, may differ between outputs and impacts. Second, the three areas to explore may yield different results depending on the academic discipline. What is true for biomedical sciences may not apply to sociology. The exploration of such differences by discipline lies outside the scope of this chapter. Finally, given the limitations mentioned, there is an overall need to be cautious with the use of metrics in this study and in the evaluation of research generally, as recently outlined in *The Metric Tide*.[69]

6.1. Competitive versus non-competitive funding

Interest in this topic stems from how different funding systems can affect research performance. Chapter 3 showed that the amount of funding is related to performance, but it can also be hypothesised that the way in which funding is distributed has an influence over performance. These effects were included in the country fixed effects of the econometric models as data are not available for them to be included separately (see Appendix A). An interesting research question remains: does competitive funding yield higher research output (and research quality) than non-competitive funding?

This question is increasingly pertinent as the literature widely acknowledges a trend towards more competitive funding in European and Western countries.[70] Governments have progressively shifted from traditional allocation or block funding of universities and public research institutions to a competitive system for specific research projects through research councils, shaping a dual system of allocation between core and competitive funding.[71] According to a study led by the European Commission's Joint Research Centre (JRC) on over 200 research-active universities from 33 European Research Areas (ERA), 70 per cent of total university income comes from government allocations and among those, about 20 per cent, on average, is assigned on a competitive basis.[72]

Governments increasingly base their funding allocation on output-oriented criteria (or output indicators) rather than input criteria (or input indicators).[73] As public funding is increasingly allocated on a performance basis, public agencies and universities have adopted a mission-oriented and contract-based strategy[74] and aim to achieve value-for-money and be both efficient and accountable. As a result, governments have put in place mechanisms that relate funding to performance.[75] Competitive elements

[69] J. Wilsdon et al., 'The Metric Tide: Report of the Independent Review of the Role of Metrics in Research Assessment and Management', 2015.

[70] Geuna and Martin, 'University Research Evaluation and Funding'.

[71] L. De Dominicis, S. Pérez, and A. Fernández-Zubieta, 'European University Funding and Financial Autonomy' (Brussels: European Commission, 2011), ftp://s-jrcsvqpx102p.jrc.es/pub/EURdoc/EURdoc/JRC63682.pdf.

[72] Ibid.

[73] Hicks, 'Performance-Based University Research Funding Systems'.

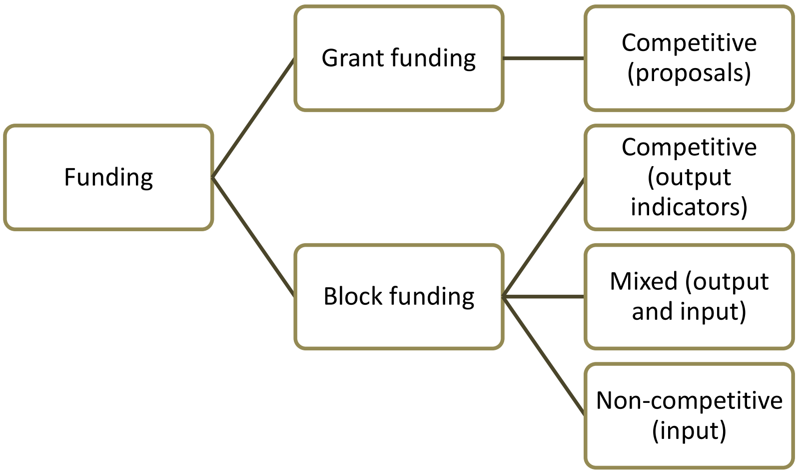
[74] Auranen and Nieminen, 'University Research Funding and Publication performance—An International Comparison'.

[75] Geuna and Martin, 'University Research Evaluation and Funding'.

have increasingly been introduced into the allocation of block funding. Many countries have adopted performance-based research funding (PBRF) as part of their national research policies.[76]

While the trend is relatively clear, the terminology surrounding the development is not as straightforward. Figure 15 shows how the different terminology could fit together and how the terms used in this study (i.e. competitive, mixed and non-competitive) relate to the wider literature. For most countries, public funding of research flows through two streams: research grants through research councils, and block funding through a ministry or special agency. In most countries, individual researchers or research groups apply for grant funding, whereas block funding is provided to universities.

Figure 15: Logic of terminology



Funding streams are classified as competitive or non-competitive, depending on the criteria on which the funding is based. Competitive funding, both grants and block funding, tends to be allocated on the basis of outputs (e.g. number of publications) or grant proposals on which researchers or institutions compete. Non-competitive funding tends to be allocated on the basis of traits that researchers or universities do not compete on, such as the total number of students or staff. Grant funding is therefore always competitive and based on proposals; and block funding can be both competitive and non-competitive, depending on the indicators that are used to allocate the funding.

Two general types of indicators can be distinguished, input indicators, such as the number of staff; and output indicators, such as the number of publications. Some block funding, such as that seen in Australia, is based on multiple indicators, some of which are competitive, such as publications; and others that are not, such as the number of staff. These block funding streams are referred to as mixed. Finally, PBRF refers to competitive funding, and for most of the literature included in Appendix C it refers specifically to competitive block funding.

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76 Performance-based research funding (PBRF), or Performance-based research systems (PBRS) as it is also called, is research funding that is allocated on a competitive basis. This can be through proposals in the case of research grants, or through the examination of indicators, such as the number of publications, for block funding as outlined in this chapter. For further information see: Hicks, 'Performance-Based University Research Funding Systems'.

This study's review of several countries finds that most countries use various funding vehicles to allocate research funding based on a mix of criteria. As such, most countries will have funding systems that combine competitive grant funding with some form of block funding. How the different countries were compared is outlined in the sections below.[77]

6.1.1. The research so far

There are a number of studies that have examined the effect of competitive funding, or PBRF, on research output and performance. Through a literature search of Web of Science and Scopus,[78] combined with additional searches through reviews of the bibliographies of relevant papers, a total of 21 relevant studies were identified. Studies were included if they provided an empirical assessment of the effect of competitive funding on research performance. The reported effects from the combined studies are shown in Table 13. Since a study can contain more than one effect, the total exceeds the 21 papers. The full list of studies is included in Appendix C. Table 13 refers to effects of both quantity (e.g. changes in number of publications) and quality (e.g. changes in citations). While these are useful concepts to distinguish between different effects, this study does not wish to propose citations as a direct indicator of research quality. As outlined in section 1.2.1, citations are only used as a proxy of research quality.

Table 13: Summary of competitive funding effects found in the literature

Effect	Frequency
Increase in the quality of publications (as measured by citations or the quality of the journal)	5
Increase in the quantity of publications (as measured by the number of publications)	14
Decrease in the quality of publications (as measured by citations or the quality of the journal)	4
No clear link	4

Note: one article can contain multiple effects; hence the totals in the table exceed the number of papers

Table 13 shows that the effects of competitive funding vary, which may be because the studies cover different systems in different countries. A substantial number of studies do find effects on the number of publications, which tends to increase when funding becomes more competitive. Out of the 14 studies that find an increase in publications, only ten also examine the effect on the quality of publications.[79] Of these ten, five find an increase in quality, four a decrease and one does not find an effect, again suggesting that the effect is not consistent. Even in the cases where there is a decrease in quality, the authors suggest that this may be linked to the incentives built into the funding system, for example, an over-emphasis on the number of publications. Must studies, apart from four, find that the funding system had an effect on the

[77] For a thorough discussion of the difficulty of measuring the impact of performance based funding and its intended and unintended consequences, see the following chapter: L. Butler, 'Impacts of Performance-Based Research Funding Systems: A Review of the Concerns and the Evidence', *Performance-Based Funding for Public Research in Tertiary Education Institutions*, 2010, 127–65.

[78] Search terms used were: "performance AND research AND funding AND publications" in Scopus and Web of Science.

[79] There are no publications that examine the effect on quality but not on the quantity of publications.

publication behaviour of researchers. Therefore, although the effects differ in direction, the incentives built into a funding system do largely seem to impact on behaviours, as is well illustrated by one detailed paper on the UK Research Assessment Exercise (RAE).

In a review of three rounds of the UK RAE (1992, 1996 and 2001), Moed[80] finds that bibliometric patterns illustrate how scientists react to the changing evaluation criteria of the RAE. At first, scientists increased their publication numbers following the inclusion of publication counts in the 1992 RAE. This increase in quantity was then followed by an increase in quality as the 1996 RAE included a focus on quality. Finally, collaborations increased towards the 2001 RAE as higher education institutions were urged to increase the number of research active staff.[81]

Although the effects of different competitive funding systems may differ in direction, the literature does seem to confirm that incentives have an effect. Depending on the type of incentive, funding systems will yield a different reaction from researchers. Given the right incentives, funding systems have potential to improve the quality of research output. However, setting the right incentives is likely to be difficult as the diversity of findings shows.

6.1.2. The current state of the data

There appear to be three ways to collect data on the effect of competitive versus non-competitive funding: (1) existing literature, mainly studies of individual countries; (2) comparative statistics from the OECD; and (3) national statistics. Each of these will be discussed in turn to address the current availability of data, their limitations, and, where possible, what future data collection would be required to improve quality.

Existing literature

In 2014 and 2015, literature on the potential effect of the introduction of increasingly competitive funding on a country's research productivity and quality expanded substantially: 13 out of the 19 relevant articles identified in this study's search are from 2014 or 2015. However, the literature is diverse, and methodologies differ in their sophistication and rigour. Some articles apply statistical models to detect changes in output (e.g. number of publications), used as a way of identifying a potential impact of

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[80] H. Moed, 'UK Research Assessment Exercises: Informed Judgments on Research Quality or Quantity?', *Scientometrics* 74, no. 1 (2008): 153–61.

[81] A recent study by Wooding et al (2015) also using both data from the RAE (2008), the REF (2014) and bibliometrics not only shows the potential to bring these different sources of data together, but also shows that between the RAE of 2008 and the REF of 2014 there was a divergence between the peer-review assessment of quality and the bibliometric assessment in medicine and the life sciences. The study also highlights the potential effect that funding systems can have on researchers, observing that 'It is plausible that changes in the financial consequences of the RAE vs. REF exercise may have influenced university submission behaviour or panel judgements. Without access to ratings of individual papers it is difficult to do more than to raise this possibility.' See: S. Wooding et al., 'UK Doubles Its "World-Leading" Research in Life Sciences and Medicine in Six Years: Testing the Claim?', *PloS One* 10, no. 7 (2015): e0132990..

competitive funding; while others are more descriptive in the review of change. Overall, the existing literature provides some insights into the potential effect of competitive funding, as discussed in section 6.1.1. Additional reviews of new literature can be added to this existing body of knowledge.

Comparative statistics from the OECD

The OECD currently collects data for one indicator that is especially tailored to capture national block funding for universities: General University Funds (GUF).[82] GUF can contribute to both research and teaching in countries such as the United Kingdom and Australia, where block grants can be used for these activities. GUF is reported in two different OECD series based on different estimation methods. First, GUF is included among the R&D expenditure data in *Research and Development Statistics*,[83] where it is based on actual R&D expenditure in a country. Second, GUF is included in the *Government Budget Appropriations or Outlays for R&D* (GBAORD) series, in which it is based on budget allocated to R&D. With regards to GBAORD, the OECD notes:

'GBAORD data are usually based on budgetary sources and reflect assessments by funding agencies. They are generally considered less internationally comparable than the perfomer-reported data used in other tables and graphs but have the advantage of being more timely and reflecting government priorities, as set out in the breakdown of funding by socio-economic objectives.'[84]

Although the GUF of GBAORD may be more up to date, it is assumed to be less comparable than the GUF of expenditure data which is based on real expenditure. However, within the GUF of the expenditure data, there are also a few observations to be made concerning comparability.

The OECD is continuously working to standardise data collection methods through revisions of the *Frascati Manual*. However, data collection on modes of funding, e.g. competitive versus non-competitive, is particularly difficult due to the differences in funding systems between countries. GUF therefore contain substantial heterogeneity in terms of the underlying data. This becomes visible through the examples presented in Table 14.

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[82] See OECD, 'Main Science and Technology Indicators', n.d., http://stats.oecd.org/Index.aspx?DataSetCode=MSTI_PUB.

[83] OECD, 'Research and Development Statistics: Government Budget Appropriations or Outlays for RD' (OECD Science, Technology and R&D Statistics, 2015).

[84] OECD, 'OECD Science, Technology and Industry Scoreboard 2011' (Paris: OECD, 2011).

Table 14: Diversity of GUF for a selection of countries

Country	GUF based on	GUF includes	Underlying funding
Canada	Financial Information on Universities and Colleges survey of the Canadian Association of University Business Officers (CAUBO)	Three major cost categories in the survey: General operating, Special purpose and trust, Capital.	The largest category, 'general operating', is mainly supported through fees.
United Kingdom	Block funding from Funding Councils	All block funding from Funding Councils	Competitive block funding from central government distributed through Funding Councils
Australia	Block funding from central government	The performance based block funding	Block funding based on competitive and non-competitive indicators from central government
France	The entire budget allocation for R&D in the universities, from both civil R&D budget and the higher education budget		

Source: OECD Metadata Application[85]

The underlying heterogeneity makes it difficult to treat GUF as an indicator that consistently measures a similar type of funding. In addition, the availability of the data also makes it difficult to use GUF as an indicator for comparative research. Data are either not available or missing for a substantial number of countries and would require multiple modifications (e.g. interpolation and extrapolation) to serve as an indicator (Table 15). With rapid changes in this area it is difficult to make such modifications without delving deep into developments in each country.

Table 15: General university funds

	1996	2000	2005	2010	2011	2012	2013
Canada	1210	1501	1893	1921	2034	1936	1930
France	2586	3711	4209	3803	3781	3657	..
Germany	6381	6275	6224	..	..	..	..
United Kingdom	1952	2250	3031	3165	3038	2892	2751
United States	N/A	N/A	N/A	N/A	N/A	N/A	N/A
China	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Source: OECD (2014) Amounts in 2005 US Dollars - Constant Prices and Purchasing Power Parities

National statistics

A third way to collect evidence on competitive versus applied funding is to construct new data series using national statistics. While the problems faced by the OECD already point to the difficulties of such an

[85] OECD, 'Metadata Application', 2015.

exercise, a short feasibility study for a selection of countries was undertaken as part of this study to assess the type of data that could be collected from national sources and to review their comparability.

Interviews with country experts revealed that substantial diversity in funding systems and data availability exists between countries. This means that while substantial and relevant information is available for some countries, much less can be gathered from others. This suggests that rather than cross-country comparative studies, it would be more useful to follow the approach of the recent literature on individual country studies.

6.1.3. Future studies and data needs

The literature shows that incentives can have an effect on researcher behaviours and that the right incentives have the potential to stimulate publications in more frequently cited journals. This does not answer the question whether or not competitive funding is more efficient or effective at generating outputs than non-competitive funding. However, the examination of the literature and the available data suggests that this may not be the most fruitful question to explore.

The literature shows that for most countries, the effect of competitive funding is measured over time as a new funding system is introduced. In most of these studies it is not possible to pitch competitive against non-competitive funding. Although it is possible to learn from the studies focusing on, for example, efficiency changes, they do not yet allow a final judgement to be made on the efficiency of both systems as it was not a controlled environment. These within-country studies can point to changes but not establish causality as different funding systems tend not to exist side-by-side within one country and each fund their own set of researchers. The alternative to within-country studies is to conduct cross-country comparative studies, however, as noted above, the current state of the data means this may not be possible. In both cases, studies would face the common problem that most researchers will have received funding from multiple sources, both competitive and non-competitive, and disentangling these is challenging, as outlined in section 2.2.1.

A possible next step for future studies, therefore, may be to understand the effect that different incentives built into funding systems have on research outputs. For the United Kingdom, for example, such a bibliometric study could focus on the incentives included in the latest Research Excellence Framework (REF). Moed examined the effect of previous Research Assessment Exercises and outlined the impact incentives had on publications.[86] A similar, but potentially more advanced study, could be conducted following the latest REF and examine the performance over the next few years of universities and university departments that performed well. Furthermore, the research performance of 'successful' universities and university departments could be examined to see whether they differ from others and whether this is a result of anticipated incentives in the REF. The bibliometric data required for such a study would include publications and normalised citations for the United Kingdom, broken down by subject category and available by university, and, if possible, university department. The subject categories

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[86] Moed, 'UK Research Assessment Exercises'.

would need a greater degree of granularity than is currently available from the BIS dataset, which only contains 26 subject categories.

The literature seems to confirm that incentives can have an effect and that competitive funding has the potential to increase, but also decrease quality. A study of this nature would, therefore, appear to be most relevant to policy making in the United Kingdom, as it would assess the impact of the actual funding system rather than address a more theoretical question regarding the effectiveness of competitive versus non-competitive funding.

6.2. Basic versus applied funding

A second area for future analysis is the difference and balance of funding between basic and applied science. Although the utility of this division can be questioned, they are concepts that frequently return in the discourse on research.[87] The question of interest in this area could be: are there any data, analysis or evidence that shows an optimal balance in basic versus applied funding that would yield higher 'returns' of the level and quality of research output (e.g. citations and Top 1%)?

As this question is not without controversy, both in phrasing and in content, several caveats need to be acknowledged. First, basic and applied sciences differ in their levels of citations; in general, basic sciences yield more citations than applied sciences.[88] From studies on medical research it has been noted that differences in citation practices in clinical and basic research are not always fully captured by bibliometric analysis.[89] This suggests that a country's relative weight in either basic or applied science could influence the level of citations, and thus would be worth taking into account as it can skew the metrics. Second, there is evidence, at least in the biomedical and health sciences, that even over a long time period (20-25 years), applied research has significantly more impact outside academia (e.g. on health and the economy).[90] These caveats show that some caution should be given to any comparison that focuses solely on academic outputs when comparing basic and applied funding.

Unlike competitive versus non-competitive funding, the aim of further analysis on basic and applied science is to explore whether there is any literature or data that could provide the basis for further analysis, such as a cross-country comparison or trend analysis over time. As it is impossible to distinguish basic

[87] For a history on the origins of the term 'basic science' see: Benoit Godin, 'Measuring Science: Is There "basic Research" without Statistics?', *Social Science Information* 42, no. 1 (2003): 57–90.

[88] N.J. Van Eck et al., 'Citation Analysis May Severely Underestimate the Impact of Clinical Research as Compared to Basic Research', *PloS One* 8, no. 4 (2013): e62395; J. Du, X. Tang, and Y. Wu, 'The Effects of Research Level and Article Type on the Differences between Citation Metrics and F1000 Recommendations', *arXiv Preprint arXiv:1501.01076*, 2015, http://arxiv.org/abs/1501.01076.

[89] Van Eck et al., 'Citation Analysis May Severely Underestimate the Impact of Clinical Research as Compared to Basic Research'.

[90] Wooding et al (2011) Project Retrosight. Understanding the returns from cardiovascular and stroke research: Policy Report (MG-1079-RS). Cambridge, RAND Europe; Wooding et al (2005) Payback arising from research funding: an evaluation of the Arthritis Research Campaign. Rheumatology 44:1145–1156; Wooding et al (2013) Mental Health Retrosight. Understanding the returns from research (lessons from schizophrenia): Policy Report (RR-325-GBF). Cambridge, RAND Europe.

from applied publications in the bibliometric dataset received from BIS, it is not possible to conduct any further analyses of this type without commissioning additional bibliometric data. There are ways to collect bibliometric data that allows for analyses that approximate such an approach; these are discussed in section 6.2.3.

6.2.1. The research so far

Although there have been some studies on the balance between basic and applied science funding,[91] very few have examined whether or not the balance between the two is 'right' or 'optimal' in a country, or whether it requires changing. A modest literature search in Web of Science and Scopus did not yield relevant papers for the keywords used.[92] Studies that aim to measure the returns to basic and applied science do exist, however these address a different research question and do not comment on what the 'optimal' balance between basic and applied funding could or should be.[93]
Three notable exceptions, identified through Google Scholar searches of the keywords, are papers by Gersbach et al., Shapiro, and Banal-Estanol et al.[94] While none of these papers directly address the 'optimal' balance, they do comment on the circumstances under which basic and applied science funding can have differential effects.

Gersbach et al. create a that includes government funding in basic research, the share of high-technology sectors in a country, and the openness of the economy to foreign investment to understand how much governments should invest in basic research. While the results differ by the degree of openness of the economy, they find that 'the closer the country is to the world's technological frontier the more the government should invest in basic research and the more the private sector will react with higher R&D expenditures.' Thus, countries that are technological frontrunners should invest in basic science as this will work as a catalyst of research in the private sector.

Shapiro argues that as basic research provides the largest spillovers, despite being the most underinvested area of research in the private sector, the US government should increase its investment in basic research to address the market failure.

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[91] G. Reid, 'Why Should the Taxpayer Fund Science and Research?' (London: University College London, 2014).

[92] Keyword search in Scopus and Web of Science did not yield much. Search terms used were:
funding AND basic AND applied AND research AND publication
basic AND applied AND research AND publication AND citation
basic AND applied AND research AND publication

[93] For example: Salter and Martin, 'The Economic Benefits of Publicly Funded Basic Research'.

[94] A. Banal-Estañol, M. Jofre-Bonet, and C. Lawson, 'The Double-Edged Sword of Industry Collaboration: Evidence from Engineering Academics in the UK', *Research Policy* 44, no. 6 (2015): 1160–75; H. Gersbach, M. Schneider, and O. Schneller, 'Optimal Mix of Applied and Basic Research, Distance to Frontier and Openness' (London: Centre for Economic Policy Research, 2010); S. Shapiro, 'Federal R & D: Analyzing the Shift From Basic and Applied Research Toward Development' (Stanford University Honors Thesis, May 2013, 2013).

Finally, Banal-Estanol et al. find that the number of publications generated through basic and applied research in engineering differ depending on the degree of public funding (i.e. through the UK Engineering and Physical Sciences Research Council [EPSRC]) and the degree of collaboration with industry. In short, they find that: "Basic research output is positively affected by the presence of EPSRC funding but not significantly affected by the degree of industry collaboration. Conversely, for applied publications we find no significant effect of the presence of EPSRC funding but a significant inverted U-shaped effect of the degree of industry collaboration." Thus, for engineering it seems that public investment in basic research are more likely to yield a higher number of publications than in applied research. This is in line with the findings in medical research.

Despite the interesting findings of these papers, none point to an 'optimal' balance of basic and applied research funding.

6.2.2. Current state of the data

There are two main data sources on basic and applied funding: the OECD and national statistics. OECD data are based on questionnaires completed by national statistics agencies and, as with some countries, uses the *Frascati manual* to make the classification into basic and applied science. National statistics may be based on the same definitions, such as in Italy and Spain, for example, and therefore provide the same figures as the OECD data. Not all countries use this data, however: Canada does not provide a breakdown for basic and applied funding, nor does Germany since 1994. This means that for these countries, neither the OECD nor the national statistics agencies are able to provide breakdowns, which limits the scope for cross-country comparative studies. In terms of data availability, it is unlikely that national statistics will provide more detailed and comparable data than are already available from the OECD.

6.2.3. Future studies and data needs

The data on basic and applied science funding is less diverse than the data on competitive and non-competitive funding, and, where available, is consistent between the OECD and national statistics. In this respect, there appears to be little scope for future data collection efforts to increase or improve the data on basic and applied funding.

In terms of research performance, however, there are changes that can be made to current bibliometric data through the introduction of research levels. A number of studies, mainly in biomedical fields, use four research levels to distinguish basic from applied journals.[95] These biomedical research levels, based on a classification first developed by CHI Research in the United States, assign journals to one of four categories: (1) clinical observation; (2) clinical observation and investigation; (3) clinical investigation; and

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[95] V. Larivière et al., 'International Comparative Performance of Mental Health Research, 1980–2011', *European Neuropsychopharmacology* 23, no. 11 (2013): 1340–47.

(4) basic biomedical research.[96] These four categories allow for the classification of journals and an investigation of research output according to research levels.

Various critiques have been levied at this classification, however, and alternatives have been suggested, one of which by Tijssen is particularly worth highlighting.[97] After a substantial critique of the basic/applied dichotomy, Tijssen[98] proposes a new classification system of journals based on what he refers to as the 'knowledge utilisation triangle'. This triangle captures the degree to which journals have an 'application orientation', which is measured by the share of papers that are co-authored by authors from either the business sector, the civil society sector or the medical sector.[99] Tijssen argues that involvement of authors from relevant sectors provides a good proxy of the degree to which the material published will be utilised in practice.

However, the classification by Tijssen, while interesting, does not appear to be readily available for wider bibliometric research. In fact, apart from the four research levels originally developed by CHI Research, bibliometric providers do not seem to work with other classification systems of research levels.[100]

A limitation to classification systems in relation to this study is the impossibility of 'linking' papers classified as either basic or applied (or otherwise through another classification system) to particular streams of funding, as outlined in section 2.2.2. As previously discussed, sources of funding can begin to be analysed through an analysis of the acknowledgement sections, however these are generally incomplete.

6.3. Capital versus resource

Research spending in the United Kingdom is divided into two categories: capital spending and resource spending. These categories are widely used within government and are generally defined as[101]:

- Capital: "Capital spending is money that is spent on investment and things that will create growth in the future."[102]

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[96] F. Narin, G. Pinski, and H. Gee, 'Structure of the Biomedical Literature', *Journal of the American Society for Information Science* 27, no. 1 (1976): 25–45.

[97] Other classifications still tend to be based around the basic/applied spectrum, such as: K. Boyack et al., 'Classification of Individual Articles from All of Science by Research Level', *Journal of Informetrics* 8, no. 1 (2014): 1–12; Du, Tang, and Wu, 'The Effects of Research Level and Article Type on the Differences between Citation Metrics and F1000 Recommendations'.

[98] R. Tijssen, 'Discarding the "basic Science/applied Science"dichotomy: A Knowledge Utilization Triangle Classification System of Research Journals', *Journal of the American Society for Information Science and Technology* 61, no. 9 (2010): 1842–52.

[99] Actual tests are run by Tijssen for two of these angles: business and medical.

[100] Based on communication between the authors and three bibliometrics providers.

[101] https://www.gov.uk/government/publications/how-to-understand-public-sector-spending/how-to-understand-public-sector-spending.

- Resource: "Resource spending is money that is spent on day to day resources and administration costs."

As with spending on basic and applied science, a question can be raised about the potentially 'optimal' balance between the two categories.

6.3.1. The research so far and what data exists

In a scoping of the literature, this study was unable to identify existing studies that address the balance of capital and resource spending.[103] A way of addressing this could be to collect data from national statistics and explore if such data allow for an analysis of the balance of spending as linked to publications and citations. However, this would not be straightforward as the country case studies show that only Italy uses the categories of resource and capital in a similar way to the United Kingdom. While other countries do identify investments in infrastructure as a separate category of spending, they do not use these two categories.

It may be possible to make an inventory of infrastructure expenditure per country, but that data would not allow for an assessment of the balance between capital and resource spending. Furthermore, the performance data currently available cannot sensibly be linked to the categories of capital and resource as publications are not the result of either capital or resource spending. The unit of analysis for this type of assessment would have to be at the aggregate level of the country in order to compare the balance of one country to another. As mentioned, this would be a challenge.

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[102] In addition, to BIS capital expenditure generally constitutes an asset that is expected to provide benefit for more than 1 year, such as buildings, equipment, fittings, ICT, loans given out, equity investments etc.(Communication with BIS).

[103] Search terms used in Scopus and Web of Science were:

capital AND resource AND funding AND research AND science

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Appendix A: Econometrics additional data

Factors included in the country fixed effects

Many variables can be relevant to a study of the relationship between research spending and research performance. Numerous country differences, as discussed in Chapter 2, can be assumed to influence the relationship, such as the share of competitive research funding and the emphasis on either basic or applied science. This study has assessed the feasibility of including a number of these factors as control variables in the analysis, however, on the basis of data availability (see Chapter 6) and the relatively short time-span covered by the bibliometric data, it has not been possible to develop control variables in all cases.

Chapter 6 discussed the share of competitive funding and the share of funding for basic and applied research as potential control variables. This appendix outlines why the bibliometric subject categories as defined by BIS (the 'BIS categories') have also been subsumed into the country fixed effects in the analysis.

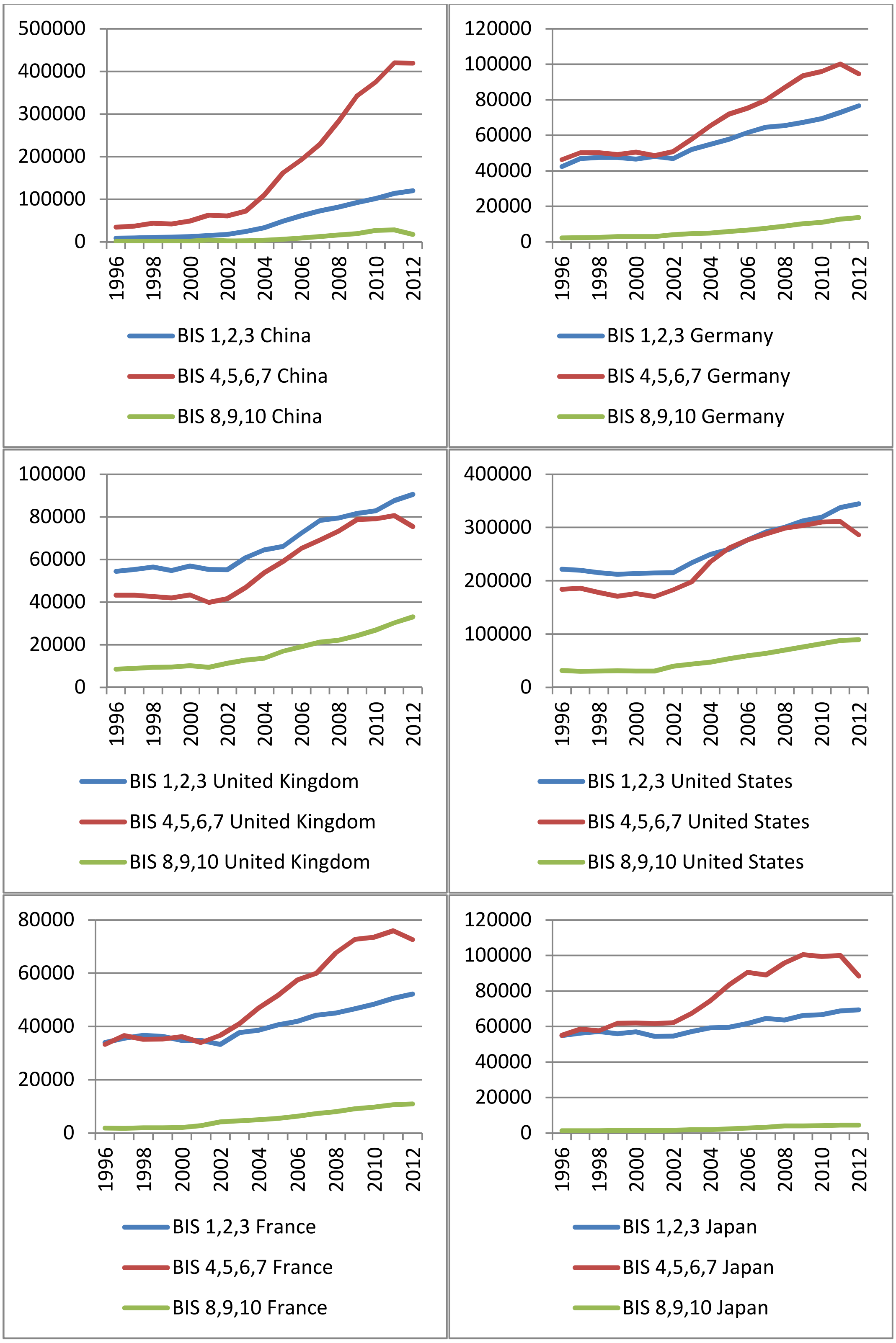
As with the differences in basic and applied research funding, countries will differ in which disciplines their research is conducted. Some countries may, for example, be more active in medicine than others. Field differences in citations are accounted for in the Field Weighted Citation Index and the top percentages of publications. However they are not accounted for in the total number of publications. Countries active in fields where high volumes of publications are the norm will have higher publication volumes than countries active in fields where lower volumes of publications are the norm. Field normalisation does not account for these differences, although the BIS categories of different fields could help take them into account. The data for these categories are complete as they are part of the original bibliometric dataset received from BIS. To broadly assess the developments of the categories, this study has merged the 10 BIS categories into 3 main categories, as outlined in Table 16.

Table 16: Merged BIS categories

BIS category	Merged category
BIS 1 - Clinical sciences	BIS 1
BIS 2 - Health & medical sciences	
BIS 3 - Biological sciences	
BIS 4 - Environmental sciences	BIS 2
BIS 5 - Mathematics	
BIS 6 - Physical sciences	
BIS 7 - Engineering	
BIS 8 - Social sciences	BIS 3
BIS 9 – Business	
BIS 10 – Humanities	

For the selected countries, the patterns of development do not differ a great deal as the time-scale of 16 years is relatively short (See Figure 16). These country differences are therefore also incorporated into the fixed effects. A deeper investigation of these category differences would be interesting, although it is outside the scope of this study.

Figure 16: Total number of publications for merged BIS categories, selected countries (1996-2012)



Countries included in the analysis

Table 17: Countries included in the econometric analysis

Countries included	
Argentina	Israel
Australia	Italy
Austria	Japan
Belgium	Luxembourg
Canada	Mexico
Switzerland	Netherlands
China	Norway
Czech Republic	New Zealand
Denmark	Poland
Spain	Portugal
Estonia	Romania
Finland	Russian Federation
France	Singapore
United Kingdom	Slovakia
Germany	Slovenia
Greece	Sweden
Hungary	Turkey
Ireland	United States
Iceland	South Africa

NOTE: These are OECD countries and other large economies. They are the countries for which the OECD collects data, and this study is limited by this selection.

Time-lag analysis for GERD

The following tables show the results for the time-lag analysis using GERD as an input, and the total number of publications and the number of publications in the Top 1% of publications as outputs.

Table 18: Unrestricted Polynomial Distributed Lag (PDL) - Fixed Effects: Publications - GERD

Lag	8	7	6	5	4	3	2	1	0
gerd	-0.2353*	-0.2353*	-0.2314*	-0.2203	-0.2201	**-0.2211**	-0.2257	-0.2689*	0.1485
	(0.134)	(0.136)	(0.135)	(0.135)	(0.135)	**(0.135)**	(0.142)	(0.146)	(0.103)
L.gerd	0.1493	0.1564	0.1657	0.1422	0.1422	**0.1472**	0.1274	0.5149***	
	(0.157)	(0.162)	(0.164)	(0.161)	(0.161)	**(0.162)**	(0.163)	(0.122)	
L2.gerd	0.1664	0.1674	0.1438	0.1524	0.1521	**0.1363**	0.4386***		
	(0.169)	(0.173)	(0.174)	(0.176)	(0.173)	**(0.173)**	(0.117)		
L3.gerd	0.2088	0.1940	0.1915	0.2001	0.2000	**0.3167*****			
	(0.167)	(0.170)	(0.171)	(0.169)	(0.168)	**(0.121)**			
L4.gerd	0.0777	0.0793	0.1027	0.1215	0.1231				
	(0.176)	(0.177)	(0.178)	(0.186)	(0.116)				
L5.gerd	0.0528	0.0730	0.1030	0.0017					
	(0.184)	(0.184)	(0.184)	(0.138)					
L6.gerd	0.0347	0.0580	-0.0928						
	(0.192)	(0.192)	(0.154)						
L7.gerd	0.0581	-0.1254							
	(0.158)	(0.126)							
L8.gerd	-0.1636								
	(0.120)								
Observations	331	331	331	331	331	**331**	331	331	331
R-squared	0.9947	0.9946	0.9946	0.9946	0.9946	**0.9946**	0.9944	0.9941	0.9937
AIC	-1163	-1168	-1173	-1179	-1186	**-1191**	-1189	-1178	-1164
SBIC	-1211	-1215	-1219	-1224	-1230	**-1234**	-1231	-1219	-1204

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.10

NOTE: In each lag model this study controls for the number of researchers in a given country, GDP per capita, and a set of time and country fixed effects.

Table 19: Unrestricted Polynomial Distributed Lag (PDL) - Fixed Effects: Top 1% - GERD

Lag	8	7	6	5	4	3	2	1	0
gerd	0.1546	0.1546	0.1627	0.1815	**0.1565**	0.1505	0.1416	0.0940	0.5203***
	(0.229)	(0.229)	(0.226)	(0.222)	**(0.222)**	(0.247)	(0.271)	(0.272)	(0.155)
L.gerd	0.1050	0.1208	0.1402	0.1006	**0.1082**	0.1373	0.0987	0.5259**	
	(0.346)	(0.349)	(0.350)	(0.330)	**(0.333)**	(0.377)	(0.395)	(0.266)	
L2.gerd	-0.0236	-0.0214	-0.0706	-0.0561	**-0.0135**	-0.1041	0.4837*		
	(0.355)	(0.361)	(0.358)	(0.358)	**(0.347)**	(0.358)	(0.269)		
L3.gerd	-0.0423	-0.0756	-0.0808	-0.0663	**-0.0543**	0.6158**			
	(0.387)	(0.403)	(0.409)	(0.405)	**(0.412)**	(0.243)			
L4.gerd	0.8535**	0.8572**	0.9061**	0.9380**	**0.7070****				
	(0.404)	(0.411)	(0.420)	(0.448)	**(0.324)**				
L5.gerd	-0.1722	-0.1270	-0.0642	-0.2357					
	(0.352)	(0.352)	(0.350)	(0.272)					
L6.gerd	0.1068	0.1590	-0.1571						
	(0.357)	(0.357)	(0.313)						
L7.gerd	0.1483	-0.2627							
	(0.267)	(0.221)							
L8.gerd	-0.3665*								
	(0.220)								
Observations	331	331	331	331	**331**	331	331	331	331
R-squared	0.9859	0.9857	0.9856	0.9856	**0.9856**	0.9850	0.9845	0.9842	0.9839
AIC	-769	-771.8	-776.8	-783	**-788.7**	-782.1	-778.5	-779.1	-779.1
SBIC	-817	-818.8	-822.8	-828	**-832.7**	-825.1	-820.5	-820.1	-819.1

Robust standard errors in parentheses

*** p<0.01, ** p<0.05, * p<0.10

NOTE: In each lag model this study controls for the number of researchers in a given country, GDP per capita, and a set of time and country fixed effects.

7. Appendix B: Case studies

This appendix provides summary descriptions of the case studies. Full case study results, with references to anonymised interviewees, have been submitted confidentially to BIS. The summaries below aim to illustrate the case studies without providing a detailed overview of the empirical material. This approach was chosen for two reasons: 1) to ensure the anonymity of the interviewees; and 2) to ensure the focus of the report remained on the exploratory nature of the conceptual framework of the case studies. Full results of the case studies could detract attention from the purpose of the case studies, that is: to explore whether the conceptual framework of cliff-edge and take-off is useful for analysing the relationship between changes in research spending and performance.

7.1. Air quality

It has been suggested that reduced research funding for atmospheric science led to a reduced capacity to detect emissions, and a missed opportunity for early and cost effective intervention. As a result, this case study aims to investigate the channels through which changes in government spending impacted research quality and performance.
Concerns about the damaging effects of air pollution levels are not a new phenomenon. The estimated costs of current air pollution levels in the UK air on NHS and the wider UK economy are valued at around £10 billion per annum. The estimated costs of current air pollution levels in the UK air on NHS and the wider UK economy are valued at around £10 billion per annum. The problem of air quality has received policy attention at the European level since the early 1970s, when Scandinavian countries started to notice the effects of acid depositions on surface waters and attributed it to pollution from the United Kingdom and central Europe. Similar evidence was found in the United Kingdom at the same time.

Air quality control is strongly driven by EU legislation, and a series of EU Directives and Council Decisions have been taken from the 1970s onwards to harmonise member states' interventions in this area. Consecutive UK governments have also introduced legislative measures to tackle air pollution problems and control emission levels. Despite these efforts, the United Kingdom has repeatedly failed to meet its emissions targets and has been sanctioned by the European Commission for not complying with its emission objectives (fines of up to £300m a year).

Several interviewees reported that the 1990s were marked by decreasing levels of government funding for experimental air pollution research in the United Kingdom. This resulted in a loss of knowledge and a reduction of the number of experiments conducted to measure air quality and better understand the levels and causes of air pollution. It has been highlighted by the interviewees that more research should have focused on assessing the effectiveness of regulations for reducing emissions and raising questions on whether reductions have affected ambient concentrations during key periods of policy implementation. Five interviewees mentioned the reasons lying behind such choices were a shift in governmental priorities at the time and a refocus of the research and policy communities' attention around issues related to climate change.

The UK air quality research landscape has been historically complex, with research taking place in Higher Education Institutions, Independent Research Organisations and government-funded laboratories. However, it was noted that the 1990s were marked by a strong relocation of air quality research activities within universities in a few influential research centres. Three interviewees noted that the closure of the Warren Spring Laboratory had been a key marker of change in air quality research activities. Other government- funded facilities were shut down or privatised.

The interviewees raised the issue that air quality research is extremely expensive, which explains why the emphasis has progressively shifted towards cheaper modelling techniques to assess air pollution levels. It was also mentioned in the interviews that the reduction of government spending for experimental research in the early 1990s also impacted the research workforce. Three interviewees noted that many researchers at the time (especially PhD students), moved away from experimental research to focus on modelling techniques. It was also noted that some researchers moved away from the field to focus their research on climate change.

Despite these changes, the interviewees also noted that UK air quality research as a whole performed well over the period of analysis, and that Research Council funding and EU funding (FP7 notably) helped maintain good research performance and partly substituted for the reduction of government spending in this area.

7.2. Nuclear Magnetic Resonance Spectroscopy

Nuclear Magnetic Resonance Spectroscopy (NMR) is a technique widely used across the sciences for the identification of the chemical and physical properties of, for example, materials, biomolecules and organisms. A distinction in techniques can be made between solid and solution state NMR, with solid state NMR generally being used less frequently than solution state NMR. The infrastructure can also be divided into these two groups. The case of NMR as a potential case study was raised amid reports and researcher testimonies that investments in NMR in the United Kingdom are lagging behind other European nations.

An inventory of NMR infrastructure available within universities in the United Kingdom was made by Smith in 2013. It showed that 133 solution state and 28 solid state NMR instruments are currently available, the majority of which are in the low to medium field range of 200-600 MHz. The United Kingdom currently has one high-field solid state NMR instrument available of 850MHz in Warwick. For solution state NMR there are several high-field facilities available in the United Kingdom (e.g. in Birmingham and London). These are largely for the bio-medical sciences.

The multidisciplinary use of NMR, and the fact that in most disciplines it is a technique rather than a topic of study, makes it difficult to identify NMR as a field to be assessed for research performance. However, through Scopus it is possible to gauge the frequency of publications referencing NMR and the disciplines within which these publications occur. Globally, the United Kingdom has been in the top five countries in terms of the volume of publications over the last 15 years. Compared to other countries, the United Kingdom therefore has a broad research base in NMR, which is, as expected, most pronounced in bio-medicine and chemistry. Based on the number of publications, the United Kingdom still has substantial capacity to conduct research. However, quantity, as discussed in Chapter 2 on bibliometrics, does not necessarily equate to quality. Although there are no further bibliometric data available for NMR publications, interviewees mentioned that NMR research in France at the European Centre for High Field NMR is deemed world leading, even if France does not produce the most publications.

Through interviews and the available documentation there appears to be a relative consensus about the research functions that different types of NMR instruments perform. Put simplistically, high-field instruments are used for the development of new techniques and the development of new fields; and medium-field instruments support the research base and enable the education of new researchers. Both are indispensable for maintaining world-leading research, although limited budgets often make balancing between the two necessary.

Strong proponents of the benefits of high-field instruments have observed their necessity for cutting-edge research. There are, however, doubts around the potential of new high-field instruments to deliver on the high expectations. Furthermore, while it does not invalidate the link between high-field instrumentation and world-leading research, it has been noted in interviews that while researchers can travel to make use of high-field instrumentation, access to medium-field instrumentation is vital on a day-to-day basis and thus needs to be in-house.

The potential competition for research funding between new high-field and existing medium and high-field instruments creates an additional funding conundrum for NMR that is often seen in relation to science investment, as the recent consultation by BIS on research infrastructure shows. While a straightforward answer to the question of 'what to fund' is not the purpose of this case study, multiple interviewees observed that in certain cases it can be easier to obtain larger sums of funding for new instruments than smaller sums of funding for the maintenance of existing infrastructure.

Through this case study, the potential consequences of not investing in NMR, and how this could translate into a cliff-edge, were explored. The first possible cliff-edge raised by the reports, and voiced in all three interviews, was the risk of not sufficiently upgrading the existing infrastructure. The second was the potential cliff-edge posed by not (sufficiently) investing in state-of-the-art instruments; this potential seemed to be less clear and less well understood. The European Centre for High Field NMR in Lyon appears to show that state-of the-art-instruments attract the world's best researchers; and travel to use such facilities is common in research. UK researchers from the pharmaceutical industry travel the world to conduct experiments on instruments that are not available in the United Kingdom and could therefore also potentially make use of these facilities. However, it is likely that they would not be able to work with such equipment in the same way as on a day-to-day basis: one expert confirmed that when researchers visit a facility for experimentation, it is never possible to run experiments as elaborately as on their own instruments. The risk remains, however, that without state-of-the-art instruments world-leading research could be lost.

7.3. Semiconductors

Interest in the case of semiconductors as a possible cliff-edge, both in terms of research and wider social economic impacts, was triggered by suggestions that the closure of plants in the North East of England followed signals from the government that semiconductors were no longer seen as a research priority. This case is therefore structured around a number of issues that need to be clarified to understand the complex set of forces that influence semiconductor industry and research.

Around the millennium, a number of plant closures by large multinationals occurred in the North East. In 1998, Siemens closed a large factory in North Tyneside, only a year after opening it, and in the same year, Fujitsu closed a plant in County Durham. Dawley[104], looking specifically at the case of Siemens in the North East, observed that the business cycles in the semiconductor industry can be quite intense, and the downturn around the millennium meant that multinationals had to make substantial cuts. The closure of the plant in Tyneside was the result, Dawley argues, of internal politics within Siemens, which made it more likely for a plant to be closed in England than in Germany. Semiconductor research in the United Kingdom therefore did not feature strongly, or at all, in decisions to either invest or disinvest in the United Kingdom. The relative separation of these plants from local research is visible in multiple ways. First, the Semiconductor Skills Tracking Survey, conducted among staff at the Siemens and Fujitsu plants, found that for the higher skilled employees particularly (supervisory and engineer), both companies relied strongly on attracting staff from outside the region, rather than locally. Second, a review of multinationals from all industries established in the North East around the turn of the century indicated that interactions of these firms with research in the region were limited.

It would be an overgeneralisation to conclude that on the basis of the examples of industry in the North East there is no link between semiconductor research and industry. From the interviews it appears that while the industry changes in the North East may not have been related to semiconductor research in the United Kingdom, the link between industry and research may still be important for high-value added companies.

It is beyond the scope of this case study to provide an assessment of the development and state of semiconductor research in the United Kingdom today, however it is still possible to outline certain trends using a variety of data sources. The interviews provided a mixed picture of the development of semiconductor research in the United Kingdom: some experts thought that semiconductor research in the

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[104] S. Dawley, ‘Making Labour-Market Geographies: Volatile Flagship Inward Investment and Peripheral Regions’, *Environment and Planning A* 39, no. 6 (2007): 1403; S. Dawley, ‘Fluctuating Rounds of Inward Investment in Peripheral Regions: Semiconductors in the North East of England’, *Economic Geography* 83, no. 1 (2007): 51–73.

United Kingdom had declined in size (e.g. number of researchers) and quality over the years; while others argued that in fact the United Kingdom has retained a strong research base.[105] In terms of publications, the United Kingdom has been very active over the last 25 years, and only over the last five years has it dropped out of the top five in terms of volume of publications. This is mainly the result of a vast increase in the number of publications coming from (East) Asia, as has also been shown in the econometric analysis. Additional bibliometric data on, for example, citations, are not available given the data limitations, and hence no further assessment of the quality of the research can be made.

Given the volume of publications produced, there is no direct reason to assume that research on semiconductors has contracted in size. However, interviewees observed, that the areas of semiconductor research in the United Kingdom have been changing and that there has been a shift in balance. A keyword analysis of Scopus revealed that over time, a trend is visible towards new topics, mainly quantum related, such as quantum dots and wells. Keywords becoming less frequent are the names of the materials being worked on (e.g. silicon, gallium, indium). These developments point to changes in the field of semiconductor research, although exactly how the field has developed is beyond the scope of this case study. Several interviewees noted, however, that semiconductor research seems to be developing into areas (e.g. quantum dots) that have not previously been associated with 'classical' semiconductor research.

7.4. Birth cohort studies research

Birth cohort studies are a type of longitudinal research where medical, economic and social information is collected on a group of individuals throughout their lives from birth. Data from these studies are used to chart health and social change and untangle the reasons behind them. These findings are not just of academic interest, they are also used to provide insights for policy development, monitor government objectives over time and predict future outcomes.

There have been four major birth cohort studies recruiting from across Great Britain or the United Kingdom: the 1946 National Survey of Health and Development (NSHD), the 1958 National Child Development Study (NCDS), the 1970 British Cohort Study (BCS70), and the 2000 Millennium Cohort Study (MCS). While there was a 12-year interval between the first three birth cohort studies, there was a gap of 30 years before the fourth birth cohort study. This 30-year gap was the motivation for this case study.

This case study can be viewed in two ways, according to interviewees. Each birth cohort study could be viewed as an individual 'take-off' event as a discrete amount of investment precipitated an uptake in research capacity and performance. However, when viewing investment from a more long-term perspective, the reduced funding between 1970 and 2000 could be considered as a cliff-edge.

Interviewees mentioned a range of reasons why it was difficult to secure funding during the 30-year gap. First, there was a lack of available funding. This was due in part to the long-term nature of these studies

[105] As evidence for the continuity of semiconductor research in the UK, one expert pointed to the fact that over the last 20 years most of the major research groups on semiconductors have remained active and have not disappeared. This view was reconfirmed through an interview with a representative from the EPSRC.

not being compatible with the fact that research funding in the United Kingdom is not usually allocated for more than five years at a time, but birth cohort studies last a lifetime. Second, as the benefits of this research are not apparent within the first few years, but instead accrue gradually over decades, it is not necessarily an investment governments wish to make as it will not yield many findings in the short term. Third, support for funding birth cohort studies during this period may have been affected by international intellectual discussions and debate in the 1960s and 1970s over whether these types of studies were useful.

Interviewees identified several consequences of the changes in funding for birth cohort studies research during the 30-year gap. First, a knowledge gap has been created as there is a generation for which a relevant birth cohort does not exist. This has also led to cross cohort studies with reduced power. Second, the reduced data collection sweeps during this period has led to reduced communication with the participants from the already existing studies. As this tends to lead to lower response rates to future data collection requests, the overall value of the already existing birth cohorts may have been affected. Third, research capacity building may have slowed down.

Attempts to recover information lost through the absence of a national cohort study during the 30-year gap have been made by analysing other longitudinal data collected during this period. This includes the British Household Panel Survey, the Next Steps study and the Avon Longitudinal Study of Parents. However, interviewees noted that the data collected from these studies does not fully compensate for having a full national cohort.

Several factors contributed to the initiation of the 2000 birth cohort study at the end of the 30-year gap. First, a series of findings in the late 1980s revealed the importance of foetal development on health in childhood and adult life. This life course perspective provided a good example of how birth cohort study findings could inform policy development. Second, there was an initiative introduced in the late 1980s to improve the quantitative skills of social scientists using longitudinal cohort data. Third, there was an increase in government funding in order to support a millennium birth cohort.

According to interviewees, infrastructure, initiatives for the harmonisation of data, and capacity building have been improved and centralised since 2000. These have been. provided by the ESRC funded Centre for Longitudinal Studies, the MRC Unit for Lifelong Health and Ageing, and the ESRC and MRC funded Cohort and Longitudinal Studies Enhancement Resources. There have been changes within the field in relation to data sharing and increased accessibility to nationally collected administrative data, which has increased the type of analysis that can be done with minimum disruption to the participants. Finally, it was observed by interviewees that there has been increased interest to support this type of research within government due to an increased general awareness of how the findings from birth cohort studies have been used to inform and monitor policy.

7.5. Soil science research

Soil science is a field of research that is becoming increasingly diverse. In common with many areas of science, interviewees observed that the term 'soil science' covers a spectrum of research, from basic, curiosity-driven research, through to applied research, which seeks to deliver solutions to societal problems. Soil is typically defined as the zone of terrestrial cover that is characterised by biological activity and is generally no more than one metre deep.

Between 1982 and 1987, when the budgets of all research councils were reduced, there was a 23 per cent fall in funding for the Agricultural Research Council (ARC). As the majority of the soil science research was funded by the ARC during this period, the cuts in ARC funding had substantial consequences on soil science researchers in the 1980s and 1990s.

It was observed by interviewees that over the last 10 to 15 years there has been a transition within the field of soil science research and that the research community has changed. As with other disciplines in environmental and biological sciences, this change has been driven by the advent of new technologies that provide big data and the increased awareness of the importance of the soil sciences for society. The transition in the soil science community is perceived as a take-off by some and a cliff-edge by others. One interviewee observed that the new subfields that have emerged are attracting increasingly more funding, while some aspects of more 'traditional' soil science are receiving less funding. From a funding body perspective it appeared that soil science is in the early take-off stages as there has been a move to funding specific soil science related strategic programmes in the last five years.

A take-off in soil science in the United Kingdom could be reflected by the 350 per cent increase in the annual number of UK soil science publications between 1999 and 2001. The global annual number of publications increased by 250 per cent in this same time period. It was suggested by one of the interviewees that while the United States is a leader in agriculture related soil science research, Europe is excelling in ecological systems soil science research. It was also observed that there is a growing contribution from the United Kingdom to ecosystems soil science.

International capacity in soil biology has grown over the last decade. For example, between 2003 and 2014 the number of attendees at similar soil biodiversity conferences more than doubled. One interviewee suggested that this may be due to it now being easier to get PhD studentships associated with soil science. While this increase in applied soil science capacity was seen as promising for the field, interviewees voiced concern that the United Kingdom may be losing capacity in the necessary traditional soil science skills required for the continuation of this take-off and may struggle to retain fundamental soil science capacity. Even if early career soil scientists with core soil science skills are nurtured, it was noted that the majority of people who have attained these skills often leave academia for jobs in industry.

Increased awareness of the environmental importance of soils and the economic consequences of disrupting soil function was observed as another factor driving a potential take-off in soil science research. These soil functions have been described as soil ecosystem services, which effectively happen 'for free'. Soil performs many different functions: it filters water; it acts as a carbon sink; it is vital for food security; it is important in flood prevention; and it is a source of antibiotic discovery. The EU published a European Soil Thematic Strategy (EU STS) policy outlining the importance of avoiding soil damage in 2006. While there is currently no UK soil strategy policy, in 2011 there was a two-day meeting in London to facilitate knowledge exchange between soil science research leaders in academia and industry in the United Kingdom. A report of the resulting discussions was submitted to the Natural Environment Research Council (NERC) to help inform their future programme development.

7.6. List of anonymous interviewees

Table 20: List of anonymous interviewees

Case study and interviewees	Background/sector
Air quality	
Interview AQ 1	Academia
Interview AQ 2	Policy (former research funding)
Interview AQ 3	Policy
Interview AQ 4	Academia
Interview AQ 5	Academia
NMR	
Interview NMR 1	Industry
Interview NMR 2	Academia (Netherlands)
Interview NMR 3	Academia (UK)
Semiconductors	
Interview SC 1	Academia
Interview SC 2	Academia/industry
Interview SC 3	Academia/industry
Interview SC 4	Funding body
Birth cohort studies	
Interview BCS 1	Research funding
Interview BCS 2	Academia
Interview BCS 3	Academia
Interview BCS 4	Academia
Interview BCS 5	Office of National Statistics
Soil science	
Interview SS1	Funding body
Interview SS2	Academia
Interview SS3	Academia
Interview SS4	Academia
Interview SS5	Academia

8. Appendix C: Review of literature

Study	Input/funding measure	Competitiveness measure	Research performance measure	Geography	Time	Unit of analysis	Results
Aagaard et al 2015[106]	Norwegian research funding	Introduction of the Publication Indicator in 2004	Number of publications Field weighted citation impact Highly cited papers	Norway, Denmark, Finland, Sweden	2000-2010	Country	Increase in quantity
Adams and Gurney 2010[107]	UK HEFCE (QR) funding	Change in UK funding policy to explicit performance-based research funding	Relative citation impact (weighted citations)	UK	1981-2007	Country	Increase in quality
Amara et al 2015[108]	Canadian research funding	Share of funding received from research councils	ISI web of science on publications and citations of scholars from 35 Canadian business schools	Canada	2009-2010	Scholars from 35 Canadian business schools	Increase in quantity; Increase in quality

[106] K. Aagaard, C. Bloch, and J. Schneider, 'Impacts of Performance-Based Research Funding Systems: The Case of the Norwegian Publication Indicator', *Research Evaluation*, 2015, rvv003.

[107] J. Adams and K. Gurney, 'Funding Selectivity, Concentration and Excellence: How Good Is the UK's Research?' (Higher Education Policy Institute Oxford, 2010), http://www.hepi.ac.uk/wp-content/uploads/2014/02/46-Funding-selectivity-concentration-and-excellence-full.pdf.

[108] N. Amara, R. Landry, and N. Halilem, 'What Can University Administrators Do to Increase the Publication and Citation Scores of Their Faculty Members?', *Scientometrics* 103, no. 2 (2015): 489–530.

Anderson et al 2014[109]	New Zealand research funding	The impact of evaluation rounds, the Performance Based Research Fund	Number of pages published Journal quality	New Zealand	2000-2011	All economics staff in New Zealand	Increase in quantity; Decrease in quality
Auranen and Nieminen 2010[110]	HERD	1. Qualitative descriptive measure 2. General University Funds (i.e. internal funding) as percentage of HERD	Total number of publications	Australia, Denmark, Finland, Germany, the Netherlands, Norway, Sweden, UK.	1981-2000	Country	No clear link
Beerkens 2013[111]	Australian research funding	Changes in the Australian research funding system towards performance-based research funding	Number of publications Competitive research income	Australia	1980-2005	Country	Increase in quantity
Butler 2003[112]	Australian research funding	Change in Australian funding policy towards output based funding.	Number of publications by Journal impact quartiles	Australia	1980-2000	Country	Increase in quantity; Decrease in quality
Cattaneo et al 2014[113]	Italian research funding	Change in Italian funding policy, introduction of performance-based research funding	Publications of faculty members	Italy	1999-2011	Sample of 75 universities	Increase in quantity
Fiala 2013[114]	Czech research funding	Changes in Czech policy and funding system towards performance-based research funding	Number of publications	Czech Republic	2008-2011	21 Czech universities	Increase in quantity

109 D. Anderson and J. Tressler, 'The New Zealand Performance-Based Research Fund and Its Impact on Publication Activity in Economics', *Research Evaluation*, 2013, rvt017.

110 Auranen and Nieminen, 'University Research Funding and Publication performance—An International Comparison'.

111 M. Beerkens, 'Competition and Concentration in the Academic Research Industry: An Empirical Analysis of the Sector Dynamics in Australia 1990–2008', *Science and Public Policy*, 2012, scs076.

112 Butler, 'Impacts of Performance-Based Research Funding Systems'.

113 M. Cattaneo, M. Meoli, and A. Signori, 'Performance-Based Funding and University Research Productivity: The Moderating Effect of University Legitimacy', *The Journal of Technology Transfer*, 2014, 1–20.

Gilhus and Sivertsen[115] 2010	Norwegian research funding	Introduction of the Publication Indicator in 2004	Number of publications Quality of the journal	Norway	2004-2007	Norwegian universities	Increase in quantity; Increase in quality
Hammarfelt and de Rijcke 2014[116]	Swedish research funding	The implementation of the national model for resource allocation in 2009 and the introduction of a system for allocating resources based on performance measures at Uppsala University in 2011	Number of publications Type/language of publication	Sweden	2006-2013	University of Uppsala	Increase in quality

[114] D. Fiala, 'Science Evaluation in the Czech Republic: The Case of Universities', *Societies* 3, no. 3 (2013): 266–79.

[115] N. E. Gilhus and G. Sivertsen, 'Publishing Affects Funding in Neurology', *European Journal of Neurology* 17, no. 1 (2010): 147–51.

[116] B. Hammarfelt and S. de Rijcke, 'Accountability in Context: Effects of Research Evaluation Systems on Publication Practices, Disciplinary Norms, and Individual Working Routines in the Faculty of Arts at Uppsala University', *Research Evaluation*, 2014, rvu029.

Himanen et al 2009[117]	HERD	[Qualitative measure] 1. The input–output orientation of direct government funding for research; and 2. The shares of internal research funding (direct government funding and universities' own funds) and external research funding (all other funding sources). The more output-oriented the direct government funding and the larger the share of external research funding, the more competitive the university funding environment is.	1. Publications per the country's higher education sector R&D expenditure; 2. The share of the country's higher education sector of OECD14[118] publications; and 3. The share of the country's higher education sector of OECD14 citations.	Australia, Finland, the Netherlands, Norway, UK	1987-2006	Country	No clear link
Hodder and Hodder 2010[119]	New Zealand research funding	Changes in New Zealand's funding system towards performance-based research funding	Number of publications Publications in quality journals	New Zealand	2004-2008	Country	Increase in quantity; Decrease in quality
Ingwersen and Larsen 2014[120]	Danish research funding	Introduction of performance indicator	Number of publications Citations	Denmark	2000-2012	Country	Increase in quantity

117 L. Himanen et al., 'Influence of Research Funding and Science Policy on University Research Performance: A Comparison of Five Countries', *Science and Public Policy* 36, no. 6 (2009): 419–30.

118 OECD14 refers to OECD15 countries (Austria, Canada, Denmark,Finland, France, Germany, Ireland, Italy, Japan, Korea, Portugal, Spain, Sweden, United Kingdom and United States) excluding the United States.

119 A. Hodder and C. Hodder, 'Research Culture and New Zealand's Performance-Based Research Fund: Some Insights from Bibliographic Compilations of Research Outputs', *Scientometrics* 84, no. 3 (2010): 887–901.

120 P. Ingwersen and B. Larsen, 'Influence of a Performance Indicator on Danish Research Production and Citation Impact 2000–12', *Scientometrics* 101, no. 2 (2014): 1325–44.

Jimenez-Contreras et al 2003[121]	Spanish research funding (% of GDP)	Change in Spanish funding policy towards performance based research funding	Number of publications	Spain	1974-2000	Country	Increase in quantity
Moed 2008[122]	UK HEFCE (QR) funding	Change in RAE criteria	Number of publications Field weighted citation impact	UK	1985-2003	Country	Increase in quantity; Increase in quality
Moore et al 2002[123]	UK HEFCE (QR) funding	Multiple RAE rounds	Number of publications	UK	1000 economists at 60 departments	Country	Increase in quantity
Osuna et al 2010[124]	Spanish research funding and number of researchers	Interrupted time-series analyses and control groups	Number of publications	Spain	1980-2005	Country	No clear link
Smart 2009[125]	New Zealand research funding	Changes in New Zealand's funding system towards performance-based research funding	Number of publications	New Zealand	1997-2006	Country	Increase in quantity
Tammi 2008[126]	Finnish research funding	Changes in the Finnish funding system towards performance-based research funding	Number of publications	Finland	1981-2005	Country	Decrease in quality

121 Evaristo Jiménez-Contreras, F. de Moya Anegón, and E. López-Cózar, 'The Evolution of Research Activity in Spain: The Impact of the National Commission for the Evaluation of Research Activity (CNEAI)', *Research Policy* 32, no. 1 (2003): 123–42.

122 Moed, 'UK Research Assessment Exercises'.

123 W. Moore et al., *Productivity Effects of Research Assessment Exercises* (Citeseer, 2002).

124 C. Osuna, L. Cruz-Castro, and L. Sanz-Menéndez, 'Overturning Some Assumptions about the Effects of Evaluation Systems on Publication Performance', *Scientometrics* 86, no. 3 (2010): 575–92.

125 W. Smart, 'The Impact of the Performance-Based Research Fund on the Research Productivity of New Zealand Universities', *Social Policy Journal of New Zealand* 34 (2009): 136–51.

126 T. Tammi, 'The Competitive Funding of University Research: The Case of Finnish Science Universities', *Higher Education* 57, no. 5 (2009): 657–79.

Vanecek 2014[127]	Czech research funding	Changes in Czech policy and funding system towards performance-based research funding	Number of publications Number of applications (e.g. for patents) Patents	Czech Republic, Austria, Hungary, Finland, Sweden, Norway, Belgium and Switzerland	Country	No clear link

[127] J. Vanecek, 'The Effect of Performance-Based Research Funding on Output of R&D Results in the Czech Republic', *Scientometrics* 98, no. 1 (2014): 657–81.