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More publicly funded research, more knowledge spillovers, more economic growth? An empirical analysis for German regions

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Abstract:

This paper deals with the effects of publicly funded research on regional technological progress and economic growth. We adopt a system approach and investigate the effects on all regional input factors and output by means of a flexible spatial panel VAR (SpPVAR) model. This allows us to deal with the evolutionary nature of regional dynamic processes. We further extend the existing empirical literature on the role of publicly funded research for economic development by differentiating between public research activities conducted by universities, technical colleges (Fachhochschulen) and non-university research institutes. The empirical results show that an increase in (public) third-party funds to technical colleges leads to positive effects on regional investment and employment rates as well as the human capital stock. We also find a positive link between the publication rate of non-university research institutes and regional investment and employment rates. Furthermore, an overall increase in combined public third-party funding of universities and technical colleges affects regional patent activities, the employment rate and output positively.

Keywords: Regional economic growth, publicly funded research, production function, factor inputs, multiple equation (SpPVAR) models, impulse-response functions

JEL Classifications: C33, I23, I25, R11, O38, O47

1. Introduction

Since the seminal works by Lucas (1988), Romer (1990) and Aghion and Howitt (1992), human capital and research and development (R&D) are seen as fundamental factors for economic growth at the national and regional level. Simply speaking, R&D leads to innovation and this triggers economic growth both through private returns to research and innovation as well as positive knowledge spillovers. At the regional level, the growing literature on Regional Innovation Systems (RIS) (e.g. Braczyk et al. 1998, Fritsch and Schwirten 1999) has further investigated the nexus between innovation processes and economic development by identifying and studying the transmission channels, such as the contribution of publicly funded research. The RIS literature concludes that publicly funded research institutes play a crucial role for innovation processes and regional economic growth.

In this paper, we analyze the mutual linkages between publicly funded research activities and regional economic development in Germany. The amount of public funds that are allocated to research and innovation activities in Germany is considerable. In 2013, 23.198 billion € were spent (BMBF 2016b) as a means to compensate for private under-investments in research and innovation activities (Beise and Stahl 1999). Given the significant financial input, gaining insight into the effects of these investment activities is of strong interest, scientifically as well as politically. Central questions are: Whether and to what extent publicly funded research institutes benefit the regional economy? Which regional economic factors are mainly affected by such research activities? And finally, do the effects differ among the particular research institutes?

However, while the effects of local public research on the innovativeness of firms is well studied (e.g. Jaffe 1989, Mansfield 1991), there are only a few studies examining the influence of such public research spending and activities on regional economic growth. Here, one strand of the recent literature uses case studies to analyze the demand effects of universities on regional income and employment (e.g. Glorius and Schultz 2002, Spehl et al. 2005, Glückler and König 2011), while other strands are focusing on co-operation and knowledge spillover effects observed at the firm level (e.g. Beise and Stahl 1999, Fritsch and Schwirten 1999, Audretsch and Lehmann 2005, Audretsch et al. 2005). Finally, a last strand of the recent literature analyzes the economic effects on regional outcome variables using single-equation regression models and regional data (e.g. Fritsch and Slavtchev 2007, Spehl et al. 2007, Schubert and Kroll 2013). These studies are most closely related to the analysis conducted here.

Hence, the aim of this paper is to extend the recent literature in two ways. First, with regard to the plurality of public research activities at the regional level, we take a disaggregated perspective by gathering information of the research activities of different entities (universities, technical colleges and non-university research institutes), and link these activities to a number of further economic variables such as investments and human capital indicators. Second, we use a statistical modelling approach that allows identifying interdependencies among variables in all kinds of directions, including the dependency of public research activities on regional economic factors. Hence, we are able to deal with regional evolutionary dynamics more adequately by treating all variables as endogenous and measuring the mutual medium-run effects of public research on regional economies.

To this end, a vector autoregressive (VAR) model is estimated and combined with an Impulse-Response-Functions (IRFs) analysis to capture direct as well as indirect effects of public research activities on regional economic variables as well as resulting feedback effects. To do so, the VAR model includes several variables – namely per economically active population GDP, employment, investment, human capital, innovation output as well as the number of publications and third-party funds as measures for scientific research activities. With regard to the latter, activities from universities, technical colleges (Fachhochschulen) and non-university research institutes (especially Fraunhofer and Max Planck institutes) are studied separately with regard to the link to economic variables.

The paper starts by presenting the different publicly funded research institutes in Germany and their particular characteristics. Moreover, potential spillover effects from public research and their spatial dimension are discussed (Section 2). Section 3 introduces the underlying economic theory and research hypotheses. After introducing the data (Section 4) and the econometric approach (Section 5), Section 6 presents the results of the analysis. Finally, section 7 summarizes and concludes this study.

2. Publicly funded research in Germany and recent empirical studies

Publicly funded research institutes

According to the research and innovation report 2016 of the Federal Ministry of Education and Research (BMBF), the German gross domestic expenditures on R&D (GERD) in 2013 accounted for 79.730 billion €, wherefrom 23.198 billion € were financed by public expenditures (29.1 %). Fund recipients are universities, technical colleges, non-university research institutes and also business organizations in the private sector. Especially universities and technical colleges (80.6 % of total gross expenditures of these entities) as well as non-university research institutes (83.2 % of total gross expenditures) are the major recipients. Although these types of research institutes received private R&D funds as well (BMBF 2016b, Table 1), for the purpose of this study we define universities, technical colleges and non-university research-institutes as the core publicly funded research institutes (a similar definition can be found, for example, in Beise and Stahl 1999).[1]

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[1] The *Max-Planck-Gesellschaft*, *Fraunhofer-Gesellschaft*, *Helmholtz-Gesellschaft*, *Leibniz-Gemeinschaft* and the *Akademien der Wissenschaft* are the largest publicly (co-)funded non-university research institutes. The particular research focus differ

Goldstein et al. (1995) argue that universities contribute to regional development through multiple impact channels. Besides investments in the regional physical capital stock and the creation of human capital, universities generate outputs that influence the knowledge and technological stock. They create basic knowledge, transfer existing know-how to firms and organizations and provide a basic knowledge infrastructure as well as they establish an innovative spirit within a region (Goldstein et al. 1995). Regarding their research activities, universities conduct mainly basic research activities with only moderate intentions of commercialization (Beise and Stahl 1999).

Compared to universities, technical colleges are more focused on teaching and education. They conduct, on average, less basic research, but they are more focused on applied and specialized research in similar technological sectors as regional firms (Beise and Stahl 1999). This is underlined by Fritsch and Schwirten (1999) showing that technical colleges – in contrast to universities – co-operate more frequently with firms than with other research institutes. Finally, technical colleges are designated regional actors, as they predominantly co-operate with regional firms (Beise and Stahl 1999, Fritsch and Schwirten 1999).

Non-university research institutes are mainly founded for the purpose of complementing university (basic) research and transferring knowledge to firms. While Max-Planck (MP) institutes are especially focused on the first aim by doing basic research, Fraunhofer institutes conduct mainly applied and contract-based research and foster industrial innovations (Beise and Stahl 1999). Hence, research activities conducted by technical colleges and non-university research institutes – especially Fraunhofer institutes – can be seen as more applied and less basic research-orientated compared to universities as well as they are more transfer-orientated to the industry. However, as shown by Beise and Stahl (1999) and Fritsch and

among these institutes considerably. Moreover, several federal research institutes belong to this group as well (BMBF 2016a).

Schwirten (1999), non-university research institutes do not always have an explicit regional focus of co-operating with firms.

Regional knowledge spillover channels

Publicly funded research institutes produce different forms of new knowledge – basic, applied or industry-related knowledge. Besides providing internal returns to this knowledge creation, the activities of publicly funded research institutes create knowledge spillovers to firms via several channels. For instance, Beise and Stahl (1999) emphasize the distribution of new knowledge via academic publications, joint R&D projects and co-operations, (informal) networks and contacts between public and private researchers as well as via hiring university researchers as important transfer channels. Varga (2000), among others, additionally mentions the role of spin-off firms, graduates and physical facilities (e.g. libraries) as important knowledge diffusion mechanisms.

Regarding the spatial dimension of these knowledge spillovers, neoclassical growth models emphasize the public good character of knowledge (non-excludable and -rivalry) implying that knowledge spills over frictionless across economies (e.g. Mankiw et al. 1992). However, there are several arguments that scrutinize this strong implication of frictionless knowledge spillovers: Firstly, public research institutes function as a regional "aerial" (Fritsch and Schwirten 1999, p. 81). They absorb foreign knowledge, create new knowledge and make it available within their own region (Fritsch and Schwirten 1999). Accordingly, it can be expected that knowledge spillovers have a particular local content. Secondly, Audretsch and Lehmann (2005), among others, refer to geographical (localization) theory and argue that new knowledge does not spill across space readily and gratuitously. In fact, the spatial range of knowledge spillovers running from publicly funded research inputs to private-sector research output has been discussed controversially in recent years: Beise and Stahl (1999) provide an excellent summary of the well-known arguments for the importance of spatial proximity between firms and public knowledge sources. On the one hand, such as the need for informal networks and contacts, face-to-face-communication or mutual trust to exchange tacit knowledge. On the other hand, the authors also provide arguments against the relevance of spatial proximity, for instance, related to modern information and telecommunication techniques as well as specifically for the case of Germany as subject of this analysis, the relative low distances within the country compared to larger economies such as the United States as well as the dense infrastructure network in Germany (Beise and Stahl 1999).

Effects of regional knowledge spillovers on regional economic outcomes

Recent studies have also analyzed the role of publicly funded research institutes (mainly universities and technical colleges) on regional economic outcomes. These studies can be divided into three research strands (a detailed survey of the results is given in Table A1 in the Appendix).

At first, there is a bulk of case studies analyzing the demand effects of universities on regional income and employment (e.g. Glorius and Schultz 2002, Spehl et al. 2005, Glückler and König 2011 among others). The main conclusion from these studies is that universities and technical colleges have positive effects on both regional income and on employment.[2]

Secondly, various firm-level studies focus on the (spatial) co-operation behavior between public research institutes and firms (e.g. Beise and Stahl 1999, Fritsch und Schwirten 1999) and on location decisions of firms to operate in spatial proximity to universities (e.g. Audretsch et al. 2005, Audretsch and Lehmann 2005). Analyzing survey data, Beise and Stahl (1999) find that 8.5 percent of the firms acknowledged that they would not have innovated

[2] Table 25 in the study of Glorius and Schultz (2002) as well as Table 1 in the study of Spehl et al. (2005) give an overview of further case studies.

without publicly funded research. However, spatial proximity – with the exception of technical colleges – is not as important as in the Unites States to gain from research spillovers (Beise and Stahl 1999). This is in line with the results of Fritsch and Schwirten (1999), who also conclude that publicly funded research institutes are vital for private innovation activities. Spatial proximity is seen as an advantage for establishing co-operations, with the highest share of regional co-operations being found for technical colleges (Fritsch and Schwirten 1999). Audretsch et al. (2005) highlight that spatial business decisions of firms to locate close to universities depends on scientific disciplines (social or natural science) as well as on the transfer mechanisms (via publications or number of students). According to a further study by Audretsch and Lehmann (2005), regions with universities that educate a high amount of students in social and natural sciences and produce a high number of publications (particularly natural sciences) attract more knowledge-based start-ups.

Thirdly, a further strand of literature uses data at the regional level to analyze the effects of publicly funded research institutes on various economic variables. Fritsch and Slavtchev (2007) analyze the effects of regular and external research funds on regional patent activity. While the first do not have significant effects, the latter affect regional patent applications significant positive (Fritsch and Slavtchev 2007).[3] In a case study for the German federal state of Rhineland-Palatinate, Spehl et al. (2007) emphasize that public knowledge and human capital increase gross value added significantly. Moreover, the authors find significant effects of public research on regional patent activity if the academic R&D staff from the origin region as well as from other regions is included (Spehl et al. 2007).[4] Finally, using regional data for all

[3] Table 3 in the study of Fritsch and Slavtchev (2007) summarizes the results of (international) studies focusing on the elasticities of private sector as well as of university R&D on innovation counts (patents).

[4] Table 2.1 in the study of Spehl et al. (2007) presents further regional studies.

German districts, Schubert and Kroll (2013) find positive effects of universities and technical colleges on regional GDP per capita, employment and patent activity.

The latter studies come closest to the empirical analysis conducted here. However, our approach contributes to the existing literature in two ways: Firstly, we expand the scope of publicly funded research activities to cover non-university research institutes besides universities and technical colleges and link these activities not only to per capita income but also a number of further economic variables such as investments and human capital indicators. Secondly, while most recent studies use single-equation models, we apply a flexible multiple-equations model that allows for capturing the evolutionary nature of the mutual interdependencies among public research activities on regional economic factors. Hence, we are able to examine the various cause-effect relationships while treating all variables of the multiple equation system as endogenous.

3. Theoretical considerations and predictions

While this section draws heavily on an empirical identification strategy introduced in Eberle et al. (2017) to analyze the evolution of a regional economy, the specific focus of this study demands some modifications of the empirical approach, which will be discussed in the following. Theories of economic growth are used to formulate specific hypotheses and to impose the temporal causal structure across the variables (Eberle et al. 2017). These elements will be combined in a flexible VAR model (Section 5) that allows us to model the effects of isolated variable changes (called shocks in the corresponding literature) in our regional system. The change (shock) of specific interest in this paper is the increase in publicly funded research activities.

Regional production function

The production function for each region i at time t is given by (Mankiw et al. 1992)

(1) $$Y_i(t) = K_i(t)^{\alpha} H_i(t)^{\beta} (A_i(t) L_i(t))^{1-\alpha-\beta}.$$[5]

With regard to the input factors we define labor $L_i(t)$ as (Eberle et al. 2017)

(2) $$L_i(t) = \lambda_i(t) \cdot P_i(0)e^{n_i t},$$

where $\lambda_i(t)$ is the share of people employed, $P_i(0)$ is the economically active population between 15 and 65 years and n_i is the growth rate of this population (Eberle et al. 2017). The production function in terms of per economically active population is given by

(3) $$y_i(t) = (A_i(t)\lambda_i(t))^{1-\alpha-\beta} (k_i(t))^{\alpha} (h_i(t))^{\beta}.$$[6]

As stated in Eberle et al. (2017), the output, employment and human capital can be measured empirically, while technology and physical capital are difficult to measure at the regional level. Thus, in order to avoid measurement errors, we use technological growth and capital investments instead. For the remainder of the paper, capital investments are denoted by s_k, while technological growth is denoted by g_i (Eberle et al. 2017).

Technology

We deviate from the strict assumption of equal technological growth across economies (Mankiw et al. 1992) and allow the short-term technological growth rates g_i to differ across German regions (Eberle et al. 2017).[7] To derive explicit hypotheses, we build on the endogenous growth model by Romer (1990). The Romer model adopts the public good argument of

[5] Y(t) is output, K(t) physical and H(t) human capital, A(t) is technology/knowledge and L(t) is labor.

[6] $y_i(t) = (Y_i(t)/P_i(t))$, $k_i(t) = (K_i(t)/P_i(t))$ and $h_i(t) = (H_i(t)/P_i(t))$.

[7] In the long-run perspective, which is not essential for our primarily research aim and our empirical model, we assume that technology is a public good and technological growth may be approximately the same across regions (neoclassical, competitive assumption). However, as stated for example by Temple (1999), this is an unrealistic assumption for short-run estimation. Thus, due to different regional characteristics, e.g. generated by evolutionary processes, we assume different growth rates of the regional technology.

knowledge, but allows for different technological growth rates across regions due to its interdependences with human capital devoted to the R&D-sector (H_A) (Romer 1990):

$$\dot{A} = \delta H_{A,i} A \quad \text{and} \quad \frac{\dot{A}}{A} = g_i(A) = \delta H_{A,i}, \tag{4}$$

where δ indicates a productivity parameter. However, the research sector in this model is assumed to be private, with firms that earn their living by licensing their research findings (Romer 1990). In reality, research is conducted by firms and publicly funded research institutes (see Section 2). Therefore, we distinguish between these two kinds of research activities. We denote A for the research output in the private sector (patents) and R for the public research efforts (publications, third-party funds), assuming that publicly funded research stimulates private research activities.

Based on the arguments in Section 2, we expand equation (4) by including public research to the Romer model

$$g_i(A) = \delta\, H_{A,i}\, (\Phi R_i + \tilde{R}), \tag{5}$$

with $\tilde{R}$ being the amount of available public knowledge from other regions. As stated by Fritsch and Schwirten (1999), publicly funded research institutes absorb and accumulate global knowledge. Moreover, they create new knowledge and distribute it across the economy (Fritsch and Schwirten 1999). The (exogenously given) R_i is a measure for the regional public research efforts and represents the amount of new public knowledge created within region *i*. Thus, R_i can be interpreted as a region-specific productivity parameter in the knowledge-production process.

Finally, research institutes make new knowledge available to firms. To this end, we add the parameter Φ to equation (5), because not all of the created knowledge is transferred to regional firms. We assume that Φ depends on the co-operation behavior (the need for spatial proximity for knowledge exchange) as well as on the form of the newly created knowledge (basic vs. applied knowledge).[8] Due to their focus on basic research and a rather unbounded spatial co-operation behavior (with primarily larger firms), we expect Φ to be generally lower for universities (see e.g. Beise and Stahl 1999, Fritsch and Schwirten 1999). Due to their focus on applied industry-related research, we expect Φ – compared to MP institutes – to be higher for Fraunhofer institutes (see Section 2). Finally, based on the previous arguments, Φ is expected to be highest for technical colleges.

Taken together, this leads to the first hypothesis:

H1: A positive change in regional public research output (R_i) leads to higher innovativeness / technological development (g_i) in the respective region. However, due to their focus on applied research and their co-operation behavior, we expect that this effect is particularly significant for technical colleges and non-university research institutes (particularly Fraunhofer institutes).

Physical and Human Capital

Straightforwardly, based on Mankiw et al. (1992), accumulation of physical capital is given by

(6) $$\frac{\dot{k}_i}{k_i} = s_{i,k}(A_i^{1-\alpha-\beta}\, \lambda_i(t)^{1-\alpha-\beta}\, (k_i)^{\alpha-1}\, (h_i)^{\beta}) - (n_i+l_i(t)+\delta),$$

where $l_i(t)$ is the rate of change of $\lambda_i(t)$, and accumulation of human capital is given by

$$\frac{\dot{h}_i}{h_i} = s_{i,h}((A_i(t)\, \lambda_i(t))^{1-\alpha-\beta}\, (k_i)^{\alpha}\, (h_i)^{\beta-1}) - (n_i+l_i(t)+\delta).$$

[8] Applied research may be based on the technological sectors of regional firms and it may require a higher amount of personal interaction for exchange (more tacit).

These equations imply that a (short-term) positive change in the technological growth rate $g_i t$ affects physical and human capital accumulation positively as it makes physical and human capital more effective. However, investment rates are expected to be constant and are not affected by such short-term changes (Mankiw et al. 1992). With respect to the variables used here, this leads to hypothesis 2 as:

H2: A positive change in the regional technological development (g_i) – triggered by an increased public research output (R_i) – leads to a significant positive effect on the stock of human capital (h_i), while it is non-significant regarding the investment rate of physical capital ($s_{k,i}$). This applies mainly to technical colleges and non-university research (Fraunhofer) institutes.

Employment rate

In his seminal work, Solow (1956) defines L(t) as supply of labor that is fully employed, the curve of labor supply is vertical (inelastic to wages) and exogenously growing at a constant rate n. Hence, technology change has no effect on the development of labor.[9] In order to deduce theoretical predictions, we assume perfect competition, where firms are price takers and in equilibrium labor is paid its marginal product. However, we neither assume a constant growth of labor supply nor a vertical labor supply curve.

On the one hand, technological progress may affect aggregate demand. Meyer-Krahmer (1999) describes that innovations are likely to increase the output demand due to reduced prices for goods and higher real earnings (aggregate demand shock). However, this would foster employment only in the short-run. In the long-run perspective, this would lead to an increase in prices and nominal wages, and, thus, to no more employment.

[9] Romer (1990) also assumes that the supply of labor $L_i(t)$ as well as human capital $H_i(t)$ are fixed.

On the other hand, a long-run effect can only occur if a change in the technological growth rate affects aggregate supply (labor markets, respectively). We define labor supply as a function of relative real wages (labor supply depends on the wage), which can be expressed as

(7) $$L_i(t) = (\lambda_i(t) \cdot P_i(0)e^{n_i t}) * [\left(\frac{\widetilde{w_{it}}}{p_{it}}\right)]^{\theta}, \quad \text{with} \left(\frac{\widetilde{w_{it}}}{p_{it}}\right) = \frac{\left(\frac{w_{it}}{p_{it}}\right)}{\left[\left(\frac{\sum_{i=1}^{N} w_{it}}{N}\right) / \left(\frac{\sum_{i=1}^{N} p_{it}}{N}\right)\right]}.$$

Equation (7) implies that higher relative wages in region *i* relative to the national average go along with a higher labor supply. Labor-augmenting technology (see equation 3) makes labor more effective (higher marginal productivity at each point), increases demand for labor and, thus, wages and employment (if the supply curve of labor is not vertical). Regarding the medium-run perspective, higher wages may attract more labor outside the region (inducing in-migration).

Niebuhr et al. (2012) provide a detailed survey of theoretical approaches showing how mobility may influence labor supply and demand. Neoclassical labor market theory assumes that migration mainly affects labor supply and works towards spatial convergence, because migration to high-wage regions puts the wages in these regions under pressure or – if wages are rigid – generate unemployment (Niebuhr et al. 2012). Hence, growth of labor supply would occur temporarily. However, this does not seem in line with the recent development of employment rate in Germany. For instance, Suedekum (2005) adds unemployment to a new economic geography model to show that migration also affects regional labor demand. This would lead to a (long-term) spatial polarization of wages and (un)employment rates (Suedekum 2005).

Taking these arguments together we can derive the following hypothesis:

H3: A change in regional public research output R_i of technical colleges and non-university (Fraunhofer) research-institutes increases the private regional innovation output (g_i). This has significant positive effects on the regional employment rate (λ_i) in the medium-run.

Output

According to our production function in equation (3), output growth is a function of the growth rate of human and physical capital as well as of technology and – in our extended model – of the employment rate (Eberle et al. 2017). Hence, productivity growth can be expressed as

(6) $$\frac{\dot{y}_i}{y_i} = (1\text{-}\alpha\text{-}\beta)\ \frac{\dot{A}_i}{A_i} + (1\text{-}\alpha\text{-}\beta)\ \frac{\dot{\lambda}_i}{\lambda_i} + \alpha\frac{\dot{k}_i}{k_i} + \beta\frac{\dot{h}_i}{h_i},$$

which immediately translates into our fourth hypothesis:

H4: A positive change in the regional public research efforts (R_i) triggers a positive change in the private innovation output g_i (H1), stock of human capital h_i (H2) and employment rate λ_i (H3) and leads to positive overall effects on regional economic output (y_i). As already stated above, these effects are expected to be particularly significant for technical colleges and non-university (Fraunhofer) research-institutes.

4. Data

We use panel data (2000-2011) for 258 German labor market regions. The classification of labor market regions is based on information of the Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) (Status: 31.12.2014). Table 1 presents variables and associated data sources. All factor inputs as well as GDP are used in the form of rates (intensities) and are log-transformed (Eberle et al. 2017). We further use data on public research activities: the number of publications of universities, technical colleges and non-university research institutes as well as the received third-party funds of universities and technical colleges. Unfortunately, no data on acquired third-party funds is available for non-university research institutes. Summary statistics for variables are presented in Table A2 in the Appendix.

As already mentioned by Eberle et al. (2017), the sample period is affected by the global economic crisis. Thus, we construct annual time dummies and add them to our empirical model. Missing data have been interpolated on the basis of an autoregressive process with three lags (investment rate). We assume that all data imperfections related to the qualification of employees are random and do not bias the results (see Eberle et al. 2017 for further details).[10]

< Table 1 here >

The upper middle and left part of Figure 1 illustrates the spatial distribution of publications in Germany for academic institutes (universities and technical colleges) and non-university research institutes for the period 2000 to 2011 (depicting publication shares defined as $\text{Publications}_i / \sum \text{Publications}_{\text{Germany}}$ for each labor market region). The upper right part and the lower part of Figure illustrates the relative distribution of the received third-party funds by universities and technical colleges combined as well as by technical colleges (defined as $\text{Third-Party funds}_i / \sum \text{Third-Party funds}_{\text{Germany}}$) – subdivided into total and public funding volumes. The Figure highlights that the extent of publicly funded research activities is quite heterogeneous across German regions.

< Figure 1 here >

[10] The variables *Patents*, *Publications* and *Third-Party Funds* contain zero values, implying that it is not feasible to logarithmize them. Hence, we add the value 0.25 to every observation of this variables (before normalization). Furthermore, data on third-party funds is available only on the level academic institutes. Some of these have campuses in more than one city. We assigned the third-party funds to the location of the institutes' headquarters. Given that we use labor market regions, in many cases all campuses fall within one region, but there are also some cases in which a correct regional assignment is not possible.

With regard to the statistical properties of our data, we are concerned with non-stationarity of variables over time as well as cross-sectional dependence across space, which may affect the estimation results. Thus, in order to deal with the issue of non-stationarity within our data, we apply a panel unit root test proposed by Im, Pesaran and Shin (2003) (henceforth IPS) to test for stationarity of our variables. Table 2 shows that this is a serious concern, especially for our public research variables. Thus, we detrend all variables indicating some form of non-stationarity. The results of the IPS test highlights that the detrended variables reject the null hypothesis of containing unit roots.

< *Table 2 here* >

Moreover, as shown in Eberle et al. (2017), geographical spillovers across variables may well exist. Therefore, we generate spatial lags for all variables – indicating the average values in the neighborhood of region *i* at time *t* – and include them to all regression models. To measure the spatial relationship across regions, a binary first-order neighborhood matrix is used:

(7) $$w^*_{ij} = 0 \text{ if } i = j \text{ and } i \text{ and } j \neq \text{common border}$$

$$w^*_{ij} = 1 \text{ if } i \neq j \text{ and } i \text{ and } j = \text{common border}$$

$$w_{ij} = w^*_{ij} / \sum_i w^*_{ij},$$

where w^*_{ij} is the element of an unstandardized weighting matrix and w_{ij} denotes the element of a normalized weighting matrix. We follow the approach presented in Eberle et al. (2017) and normalize the matrix elements by dividing them with the column sum of the matrix.

5. Econometric Modelling: Spatial Panel VAR and Impulse-Response Functions

To analyze the economic effects of publicly funded research institutes on various regional economic variables, we apply a spatial panel VAR (SpPVAR) model. These models have been recently proposed in different studies to analyze dynamic regional economic interdependencies (see e.g. Beenstock and Felsenstein 2007, Di Giacinto 2010, Monteiro 2010, Eberle et al. 2017, Mitze et al. 2017, Ramajo et al. 2017 among others). The SpPVAR model in this study follows the approach presented in Eberle et al. (2017) and allows to take an evolutionary perspective on the interdependencies among the included variables.[11]

Our dynamic economic system contains six equations including the dependent variables: 1) GDP per (economically active) capita, 2) physical capital investment rate, 3) higher education rate (human capital), 4) employment rate, 5) patent rate and 6) the rate of public research activities.

Eberle et al. (2017) present several estimation approaches that accounts for the dynamic panel bias (e.g. Arellano and Bond 1991, Kiviet 1995, Blundell and Bond 1998 or Everaert and Pozzi 2007). To estimate the coefficients of our regional system, we apply a bootstrap-based corrected FE estimator that was originally proposed by Everaert and Pozzi (2007). Further details about the model setup and estimation are given in the Appendix A3. The Appendix A3 also explains the use of the impulse-response function (IRF) analysis in order to meaningfully analyze the effects of "shocks" in our economic system over time.

6. Empirical Results

We focus on discussing the associated IRFs for the different effects of "shocks" to the various public research variables on per capita output and factor inputs. As a well-established standard for the analysis of structural VARs, the Choleski decomposition of the reduced form residuals covariance matrix is used for identification of the contemporaneous effects in the IRF analysis. Based on the theoretical aspects in section 3, we impose the following recursive causal ordering at time t:

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[11] We refer to this paper for a detailed derivation of the applied SpPVAR model as well as to Appendix A3 in this paper.

(8) $lhk_t \rightarrow lpr_t \rightarrow lpat_t \rightarrow linvq_t \rightarrow lemp_t \rightarrow lgdp_t$.

The recursive order in equation (8) can be interpreted as follows. The human capital variable on the left side has time lagged as well as contemporaneously effects on all other variables in the regional economic system, while feedback effects from the other variables to human capital only happen in a time-lagged fashion. Hence, human capital is the most exogenous (predetermined) variable in the system and the degree of endogeneity increases the more we move to the right side of equation (8). Thus, in similar veins, the public research variable has contemporaneously effects on all regional variables – except on the human capital variable (time lagged effects on all variables in the system). Finally, the variable on the ultimate rights side of equation (8) – GDP per economically active population – is affected by all other variables in period t but only has time lagged (feedback) effects on these variables. The ordering of the first three variables on the left side is basically based on the knowledge production function in equation (3) (see Section 3 - Technology).

Moreover, we follow Eberle et al. (2017) by expecting that contemporaneous capital investment decisions (at time t) are made ex-ante, while a change in the employment is rather made on ex-post basis. Finally, the GDP per economically active population is the result of the regional input factors and, therefore, the most endogenous variable in our system (see Section 3 – Output, Eberle et al. 2017).

Regional economic effects of publication activities

The results suggest that the responses of the various regional variables to a one-period change ("shock") in the publication activity of universities are persistently insignificant. This finding underlines the fact that universities conduct mainly basic research and rather distribute their new knowledge across regional boundaries (**H1** to **H4** are confirmed for universities). The same result applies for an aggregate change in the publication rate of universities and technical colleges.

With regard to the results of a one-period change ("shock") in the publication activity of non-university research institutes, the results of the IRFs in Figure 2 show that an increase in the publication activity has significant positive effects on the regional investment and employment rate.[12] The effects on the investment rate are immediately significant and highest at the year of the change ("shock") with an increase of the investment rate of 0.93 %. The effect becomes insignificant after roughly two years. In turn, the employment rate becomes significant after approximately one year with a maximum increase of 0.04 %. The estimated effects on the other variables are non-significant.

< *Figure 2 here* >

As stated in Section 2, Fraunhofer institutes conduct more applied and innovation-orientated R&D, while MP institutes complement mainly university research. However, we do not find any significant effects for MP and Fraunhofer institutes when we disaggregate their publication activities. The responses for a one standard deviation increase of the publication activity of these institutes are continuously non-significant. We conclude from this that the publication data seems not sufficient to detect the different effects of Fraunhofer and MP institutes. This seems to be a statistical problem caused by a rather weak average effect and an insufficient number of observations, since we find significant effects for the sum of aggregated non-university research institutes' activities.[13]

[12] All of the IRFs in this paper are based on the SpPVAR system in Table 1 and the associated estimated coefficients. The time dimension – measured by years – is displayed on the x-axis, while the intensity of a response to a one standard deviation shock is displayed on the y-axis.

[13] In addition to the MP and Fraunhofer institutes, the variable „Non-university research institutes" contains the publications of Helmholtz and Leibniz institutes as well (see Table 1).

Finally, the effects of a one standard deviation change ("shock") in the publication activity of technical colleges are also non-significant. This finding may indicate that the publication activity do not reflect the regional research efforts of technical colleges at its best. Hence, we continue with analyzing the growth effects of third-party funds received by universities and technical colleges.

Regional economic effects of third-party funds

In this section, we present the results of the SpPVAR models and the associated IRFs using the volume of acquired third-party funds of universities and technical colleges as indicator for the strength of public research efforts. Differently from the publication data, we are able to distinguish between overall and public third-party funding volumes.[14] Thus, we analyze funded research more precisely by not only detangling public actors (universities and technical colleges) but also the sources of funds.

The selected IRFs of the SpPVAR model in Figure 3 highlight the growth effects of a one standard deviation shock in third-party funding received by universities and technical colleges combined (higher education institutes). While the upper part of Figure 5 (a) illustrates the effects of the overall level of third-party-funds, the lower part (b) shows the isolated effects of public third-party funds. The upper part indicates that a positive shock in overall third-party funds does not go along with any significant changes in regional variables.

While the effects of private third-party funds are continuously insignificant, the lower part (b) indicates significant positive effects of an increase of public third-party funds on regional patent activity, employment rate and GDP per economically active population. A one unit standard deviation change ("shock") in public third-party funds leads – after a phasing-in process

[14] Unfortunately, we only have data of the third-party funds received by universities and technical colleges. Please note, total funds are the sum of private as well as of public funds and from funds provided by foundations, which are not analyzed separately in this paper.

of roughly five years – to a maximum significant increase of the patent activity of 0.15 %. Moreover, such a positive shock leads to a long lasting significant effect with a maximal annual 0.04 % increase of the employment rate and a maximal annual 0.18 % increase of the output per economically active population. These findings provide support for the hypotheses **H1**, **H3** and **H4**.[15]

< Figure 3 here >

As stated in **H1** to **H4**, we expect that the growth effects illustrated in Figure 3 are mainly driven by research efforts of technical colleges. The responses to a shock in the various components of third-party funding (overall, public, private funds) received by universities show no significant effects at all, supporting our findings for publications. This is in line with expectations based on the studies of Beise and Stahl (1999) and Fritsch and Schwirten (1999) regarding the research and co-operation behavior of universities.

In turn, the IRFs presented in the upper part of Figure 4 indicate that a change ("shock") in the overall third-party funds received by technical colleges increases the investment rate significantly (maximum of 0.9 % in the second year after the change). The effects on the employment rate and output are very small and insignificant, while the effects on the regional patent activity (after a phasing-in of roughly one year) and the human capital are positive (both are statistically insignificant, though).

Similar to the overall results for the academic institutes, private funds allocated to technical colleges do not have any significant effects. In turn, a positive shock in public third-party funds to technical colleges increases, on average, the stock of human capital (maximum 0.12 %) and the employment rate (0.06%) significantly (**H2** and **H3** confirmed). In contrast to the

[15] This supports the results of Schubert and Kroll (2013), who find also significant net effects on the GDP per capita, the unemployment and the patent rate (but not triggered by public third-party funds).

findings for public third-party funds received by all academic institutes (Figure 3), we find positive, but insignificant effects on the regional patent activity and the output here (**H1** and **H4** not confirmed).

< *Figure 4 here* >

Table 3 summarizes the results of the analysis conducted in this paper. We find at least some support for effects of public research activities on all five studied economic variables, namely investment, employment rate, stock of human capital, patent activity and economic output. Hence, our hypotheses are all, at least, partly confirmed. However, some details in the results are interesting.

First, we find little effects of publication activities. Publications seem not to reflect the interaction with the regional economy well. Publications are a more adequate measure for basic research, which is less regional bounded and less connected to the economic activity. In the case of public non-academic research institutes, publications have been the only available measure. As a consequence, we are not able to detect the potentially different effects of Fraunhofer and Max Planck institutes. Nevertheless, we have been able to detect some positive effects of these research institutes.

Second, the results show that technical colleges have a stronger positive effect on the regional economy than universities. In all analyses that are conducted only with universities no significant effects are found. For technical colleges a number of positive effects are detected. Hence, the higher relevance of technical colleges for the regional economy is clearly confirmed.

Third, distinguishing between public and private third-party funds leads to an interesting result: We do not find any positive effect of private third-party funds. One could have been expected that private third-party funds come to a large extent from firms and therefore signal applied research. However, public third-party funds are those that stand for a clear positive effect on the regional economy. Our interpretation is as follows. Nowadays many public research funds are given on joint innovation projects, mainly joint projects between companies and public research institutes (including universities and technical colleges). It might well be that especially these joint research projects build a connection between public institutes and private actors, often within a region, that finally leads to economic effects. As a consequence, we are able to also find positive effects of such publicly funded research on the regional patent activity and economic output

< *Table 3 here* >

7. Conclusions

This paper has analyzed the economic effects of publicly funded research in Germany. We have extended the recent literature by including non-university research institutes into consideration – besides universities and technical colleges – when analyzing the linkages between publicly funded research activities and regional economic variables. By applying a SpPVAR approach, we explicitly consider the simultaneous and evolutionary relationship across the regional variables. The associated IRFs illustrate the medium-run effects of public research activities on the regional economy.

The results do not provide any evidence that research conducted in universities does have an immediate effect on the economic activity within the surrounding region. This is in line with theoretical expectations and may reflect their focus on basic research and mainly inter-regional co-operations. In turn, we find significant positive effects of the research activity of non-university research institutes. An increase in the publication rate stimulates regional investments as well as the employment rate positively. We are not able to detect differences between Fraunhofer and MP institutes, which might well be a data issue. Hence, this topic should be taken up with better data in the future.

Furthermore, we find that especially public third-party funds have positive effects on the regional economic activity. This might be caused by the fact that often public funds are given to collaborations between private actors and academic institutes. Hence, we conclude that such funds might be especially helpful to make public research institutes effective within their region. The clear results for technical colleges compared to universities can be interpreted such that technical colleges use the collaboration potential within the region more extensively.

From this we might draw the following policy implication: If we want to see more regional economic effects of public research institutes, the direct interaction with companies has to be increased. Public funds for collaborations of these actors seem to be a good tool for increasing the regional effects. The regional effects of universities seems to be low so far, but this might change if the collaboration behavior of universities changes.

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9. Acknowledgements

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Tables

Table 1: Variables and used data

Variable	Description	Data source
lgdp	**GDP per economically active working population** (in logs) defined as: [GDP in € / (Population aged between 15 and 65 years * Participation rate)] **Note:** Population data is based on the extrapolation of the census 1987. The participation rate is based on the same population data till the year 2011. From 2011, the participation rate is calculated based on the population data of the census 2011.	**GDP:** Arbeitskreis "Volkswirtschaftliche Gesamtrechnungen der Länder" (Status: August 2015) **Population aged between 15 and 65 years:** Regionaldatenbank Deutschland (Based on the population census 1987) **Participation rate:** Statistik der Bundesagentur für Arbeit / Indikatoren und Karten zur Raum- und Stadtentwicklung (INKAR)
linvq	**Private-sector investment rate** (in logs) defined as industry investments in the manufacturing, mining and quarrying sector as share of the nominal GDP: [Industry Investments in € / GDP in €] **Note:** Missing values have been interpolated on the basis of an autoregressive process with 3 lags.	Bundesinstitut für Bau-, Stadt-, und Raumforschung (BBSR), laufende Raumbeobachtungen, various issues
lhk	**Higher education rate** (in logs) defined as: [Employees with university degree / (Population aged between 15 and 65 years * Participation rate)].	Institute for Employment Research (IAB), Nuremberg
lemp	**Gross employment rate** (in logs) defined as: [Employees total / (Population aged between 15 and 65 years * Participation rate)]	Institute for Employment Research (IAB), Nuremberg
lpat	**Patent rate** (in logs) defined as:	Own calculation from the PATSTAT

	[Patents / ∑ Patents Germany]	database (Version October 2014, European Patent Office)
lpubli	**Publication Rate** (in logs) defined as: [Publications / ∑ Total Publications Germany] **Note:** Non-academic research institutes contains the publications of MP, Fraunhofer, Helmholtz and Leibniz institutes.	Own calculation from the Web Of Science database
ltpf	**Third-Party Funds Rate** (in logs) defined as: [Third-Party-Funds / ∑ Third-Party Funds Germany] **Note:** Public third-party funds are the sum of funds from the Bund, Federal States, municipalities, German Federal Labor Market Authority, Deutsche Forschungsgemeinschaft (DFG), EU and other public investors (the dataset contains one negative value of the public third-party funds, which was replaced by 0.25). Total Funds are the sum of private and public funds as well as from funds from foundations.	Statistisches Bundesamt (Deutschland)
w_X	**Spatial lag for variable X** are constructed with the STATA command *splagvar*. All spatial lag variables have been normalized and log-transformed	

Table 2: Unit Root Test

Variable	Number of regions	Number of years (2000-2011)	IPS test-statistic	p-value
Regional economic variables				
lgdp	258	12	-4.1221	0.000
lemp	258	12	-0.3447	0.3652
lemp_detrended	258	12	-16.0799	0.000
lhk	258	12	0.1299	0.5517
lhk_detrended	258	12	-17.6164	0.000
linvq	258	12	-17.5815	0.000
lpat	258	12	-17.7583	0.000
w_lgdp	258	12	-3.3759	0.0004
w_lemp	258	12	-1.4097	0.0793
w_lemp_detrended	258	12	-17.7560	0.000
w_lhk	258	12	0.0105	0.5042
w_lhk_detrended	258	12	-18.1141	0.000
w_linvq	258	12	-15.1902	0.000
w_lpat	258	12	-13.6839	0.000
Publicly funded reserach variables - Publications				
lpubli_acad	258	12	4.0154	1.0000
lpubli_acad_detrended	258	12	-23.7844	0.000
lpubli_uni	258	12	-2.4321	0.0075
lpubli_fh	258	12	5.0245	1.0000
lpubli_fh_detrended	258	12	-24.1913	0.000
lpubli_ri	258	12	21.2632	1.0000
lpubli_ri_detrended	258	12	-16.7852	0.000
lpubli_fraun	258	12	30.7204	1.0000
lpubli_fraun_detrended	258	12	-21.6987	0.000
lpubli_mp	258	12	-11.2066	0.000
w_lpubli_acad	258	12	-8.7441	0.000
w_lpubli_uni	258	12	-11.0235	0.000
w_lpubli_fh	258	12	-20.3274	0.000
w_lpubli_ri	258	12	-0.5396	0.2947
w_lpubli_ri_detrended	258	12	-25.5118	0.000
w_lpubli_fraun	258	12	-1.5068	0.0659
w_lpubli_fraun_detrended	258	12	-26.8939	0.000
w_lpubli_mp	258	12	-14.5027	0.000
Publicly funded reserach variables - Third-Party Funds				
ltpf_acad	258	12	16.4138	1.0000
ltpf_acad_detrended	258	12	-9.0859	0.000
ltpf_acad_pub	258	12	16.4347	1.0000
ltpf_acad_pub_detrended	258	12	-7.7343	0.000
ltpf_uni	258	12	13.8219	1.0000
ltpf_uni_detrended	258	12	-18.5124	0.000
ltpf_uni_pub	258	12	12.8061	1.0000
ltpf_uni_pub_detrended	258	12	-30.7130	0.000
ltpf_fh	258	12	18.0493	1.0000
ltpf_fh_detrended	258	12	-17.4842	0.000
ltpf_fh_pub	258	12	13.7382	1.0000
ltpf_fh_pub_detrended	258	12	-10.1657	0.000
w_ltpf_acad	258	12	-3.4084	0.0003
w_ltpf_acad_pub	258	12	-5.2830	0.000
w_ltpf_uni	258	12	1.6142	0.9468
w_ltpf_uni_detrended	258	12	-20.8315	0.000
w_ltpf_uni_pub	258	12	-0.5232	0.3004
w_ltpf_uni_pub_detrended	258	12	-21.4567	0.000
w_ltpf_fh	258	12	-7.5905	0.000
w_ltpf_fh_pub	258	12	-10.1677	0.000

Notes: IPS: Im et al. (2003) panel unit-root test. H0: All panels contain unit roots. HA: Some panels are stationary. Suffix "_detrended" denotes detrended variable; see text for details.

Table 3: Summary of the results of the various SpPVAR models and the associated IRFs

Effects of the Publication Rate					
	PAT	**HK**	**INVQ**	**EMP**	**GDP**
Academic Institutes	o	o	o	o	o
Universities	o	o	o	o	o
Technical Colleges	o	o	o	o	o
Research Institutes	o	o	+	+	o
MP Institutes	o	o	o	o	o
Fraunhofer Institutes	o	o	o	o	o

Effects of Acquired Third-Party Funds					
	PAT	**HK**	**INVQ**	**EMP**	**GDP**
Academic Institutes - Total TPF	o	o	o	o	o
Academic Institutes – Public TPF	+ (contemporaneous effect is significant negative)	o	o	+	+
Universities – Total TPF	o	o	o	o	o
Universities – Public TPF	o	o	o	o	o
Technical Colleges – Total TPF	o	o	+	o	o
Technical Colleges – Public TPF	o	+	o	+ (contemporaneous effect is significant negative)	o

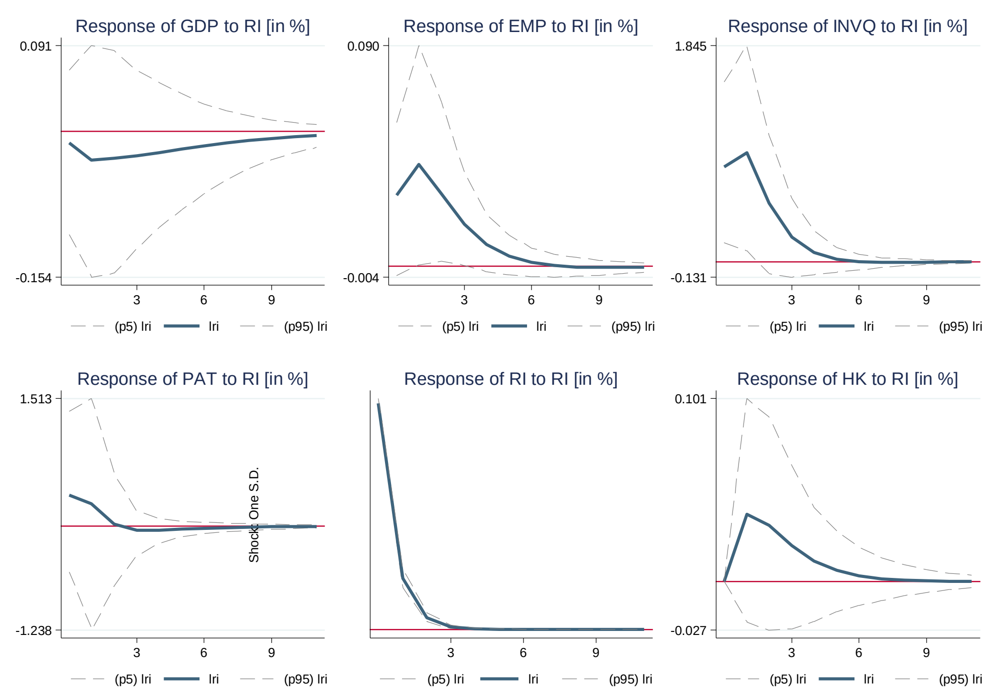
Notes: o indicates insignificant and + significant positive effects.

Figures

Figure 1: Spatial distribution of publications and third-party funds 2000 to 2011

Notes: Own figures based on data from ? (Original data, variables are not added together with 0.25)

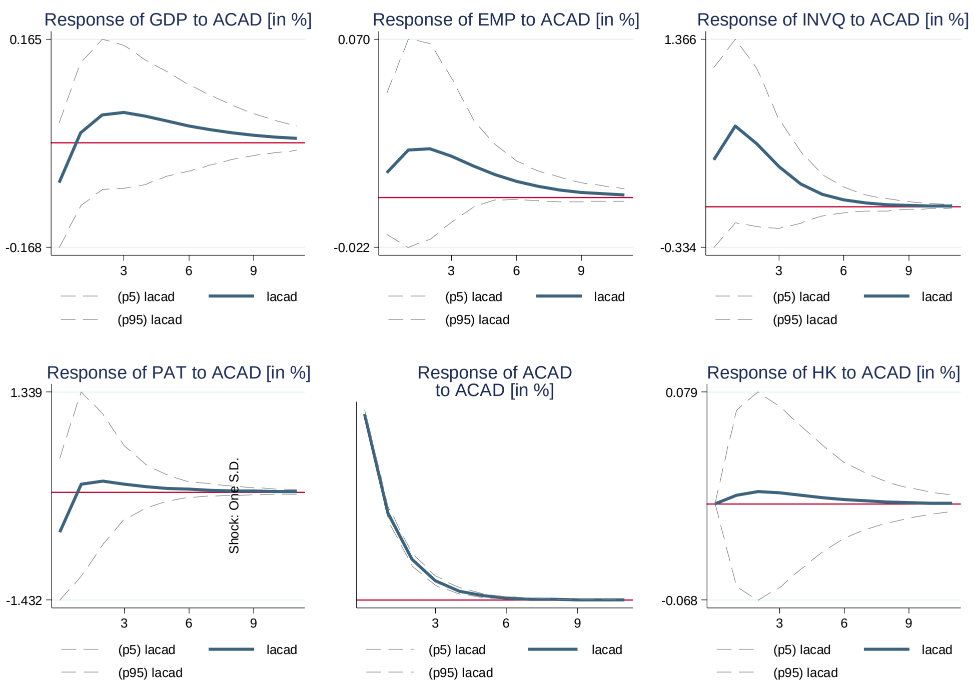
Figure 2: IRFs for response of variables to shock in publication activity of non-academic research institutes



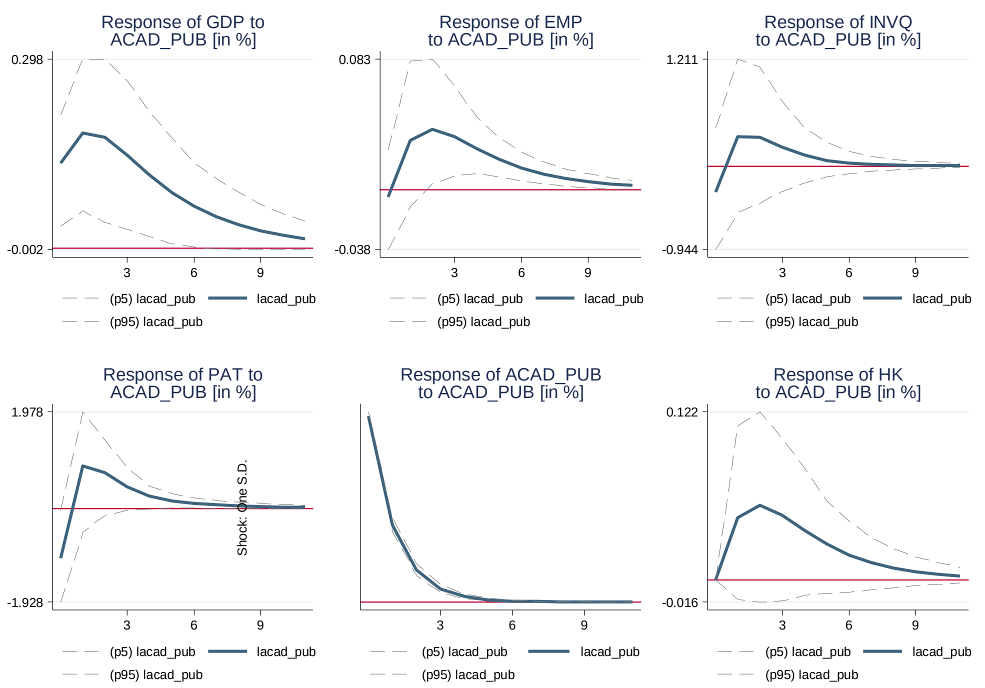
Notes: Impulse response functions are based on the SpPVAR system in Table 1 and the associated estimated coefficients. Solid lines are IRFs and dashed lines are 95% confidence intervals generated from Monte Carlo simulations with 200 repetitions.

Figure 3: IRFs for response of variables to shock in third-party funds of Academic Institutes

a. *Overall third-party funds*



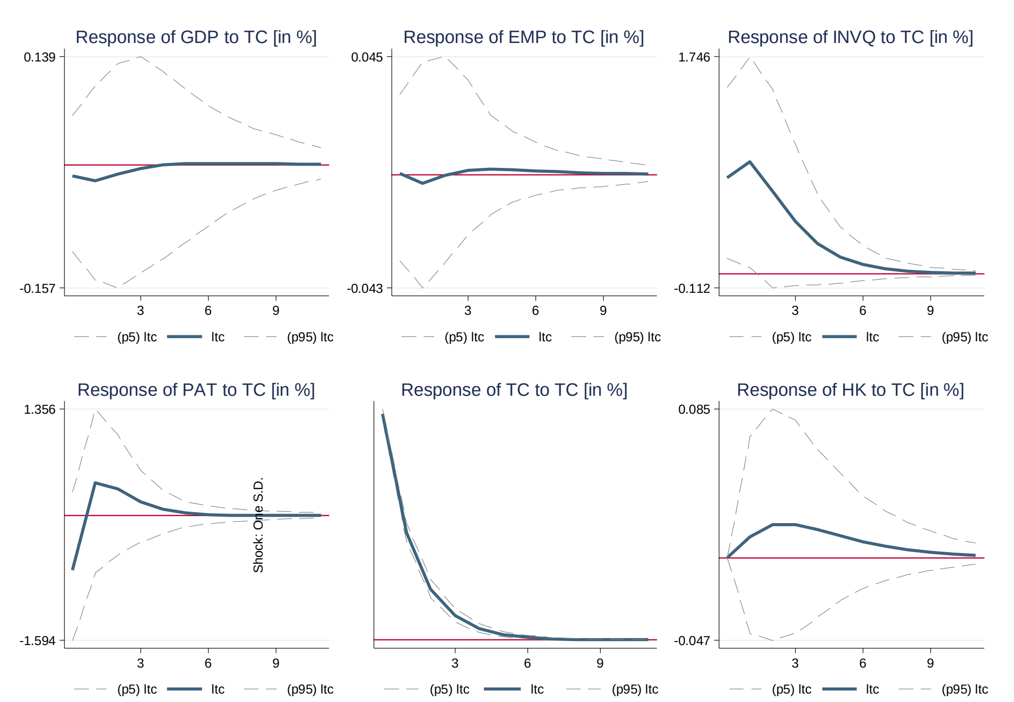
b. *Public third-party funds*



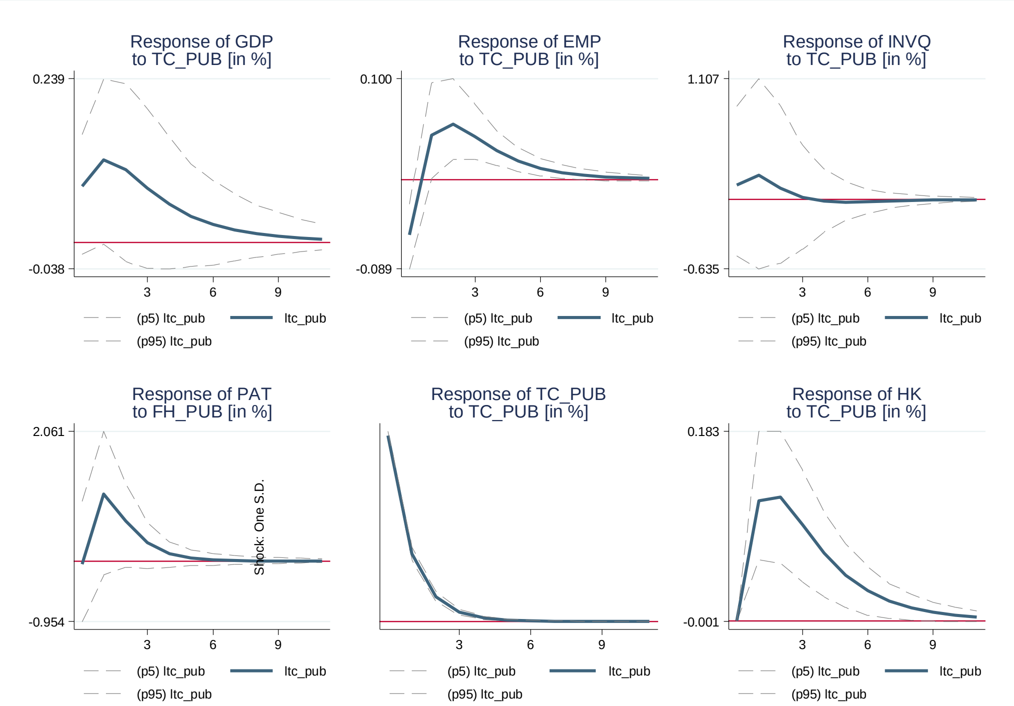
Notes: Impulse response functions are based on the SpPVAR system in Table 1 and the associated estimated coefficients. Solid lines are IRFs and dashed lines are 95% confidence intervals generated from Monte Carlo simulations with 200 repetitions.

Figure 4: IRFs for response of variables to shock in third-party funds of technical colleges

a. Overall third-party funds



b. Public third-party funds



Notes: Impulse response functions are based on the SpPVAR system in Table 1 and the associated estimated coefficients. Solid lines are IRFs and dashed lines are 95% confidence intervals generated from Monte Carlo simulations with 200 repetitions

Appendix

Table A1: Overview of recent empirical studies on the effects of public funded research institutes

Authors	Data and econometric approach	Regional Units	Dependent or Outcome Variable(s), Questionnaire question(s)	(Significant) Effects
Beise and Stahl (1999)	Cross-sectional data (1993-1996), Probit model (Maximum-Likelihood-Estimator (MLE)), multiple linear regression model (Ordinary Least Squares (OLS) Estimator)	Approximately 2300 firms from the Mannheim Innovation Panel (MIP)	*Depended variables*: public-research-based innovation, Distances between firm and the public research institute *Questionnaire*: Share of companies with innovations which could not have been developed without recent public research (%) between 1993 and 1996; Distribution of sources without which innovations from 1993 to 1996 could not have been developed (%); Size distribution of firms with innovations introduced between 1993 and 1996 which could not have been developed in the absence of public research (%); Average share of sales of new products, which could not have been developed in the absence of public research (%); Estimated sales with new products introduced between 1993 and 1996, which would not have been developed without public research, Distance between firm and cited public research institution	Public research contributes to product and process innovations of firms in Germany. Especially the size of firms and their own research intensity increase the probability of innovations related to public research. Proximity to research institutes is only of minor importance, only technical colleges are more likely to have a regional priority.

Table A1: Overview of recent empirical studies (continued)

Authors	Data and econometric approach	Regional Units	Dependent or Outcome Variable(s), Questionnaire question(s)	(Significant) Effects
Fritsch and Schwirten (1999)	1020 Questionnaires filled out by professorships at universities, technical colleges and non-university public research institutes (overall response rate 41 %), Chi-square tests	3 Regions: Baden, Hannover-Brunswick-Göttingen, Saxony	*Questionnaire*: Forms of co-operation between public research institutions and private firms, Co-operation between public research institutions and private firms by type of innovation and stage of the innovation process, Regional distribution of the co-operation partners, Forms of co-operation between public research institutions, Regional distribution of co-operation partners (other public research institutions)	Publicly financed research institutes do contribute to the innovation process of firms (mostly to early stages by developing new ideas). Co-operations across publicly funded research institutes are important as well, especially for universities. Spatial proximity is more important for co-operations between public and private actors, than across public institutes. This applies especially for technical colleges.
Glorius and Schultz (2002)	Case Study Martin Luther University Halle-Wittenberg	Administrative district Halle	*Outcome variables*: Regional income and employment effects	Regarding direct and indirect effects, the existence of the university contributes to an income of 369.1 Mio. DM per year and facilitates 7.060 jobs.
Audretsch, Lehmann and Warning (2005)	Cross-sectional data (1997-2002), multiple linear regression model (OLS Estimator and Least Absolute Deviation (LAD) Estimator)	281 high-technology firms	*Dependent variable*: Distance (kilometers of a firm to the closest university): natural logarithm, absolute number of kilometers, Median and 92% percentile.	Geographical proximity to universities matters for firm location. Firms locate closer to universities the more publications they have in social sciences and the more students they educate in natural sciences. In turn, higher publications in natural sciences and students in social sciences allow firms to locate more far away from universities.

Table A1: Overview of recent empirical studies (continued)

Authors	Data and econometric approach	Regional Units	Dependent or Outcome Variable(s), Questionnaire question(s)	(Significant) Effects
Audretsch and Lehmann (2005)	Cross-sectional data (1997-2002), Binominal regression model (MLE)	281 high-technology firms	*Dependent variable*: Number of firms located closest to a university	The results emphasize that start-ups locate often within spatial proximity to universities. The number of firms closely located to a university is positively influenced by the number of students in natural and social sciences as well as of the publications in natural science.
Spehl et al. (2005)	Case Study Federal State Rhineland-Palatinate	Federal State Rhineland-Palatinate	*Outcome variables:* Turnover, value added and employment effects	The multiplier analysis (in parenthesis: Input-Output-Analysis) shows that the total turnover effect amounts to 1.480 million € (1.280 Mio. €), while the value adding effect is approximately 890 million € (440 Mio. €). Finally, 20.240 (18.650) full time jobs are created.
Fritsch and Slavtchev (2007)	Panel data (1995-2000), sum of private sector and university R&D for neighboring regions (50 km and 50-75 km radius) are included, multiple negative-binomial regression model (Fixed- (FE) and Random Effects (RE) Estimator)	West German NUTS-3 regions (Kreise)	*Dependent variable*: Patent applications	Regular funds to universities (sources for teaching, training or equipment) that are allocated based on the amount of personnel and students, do not have significant effects. External funds to universities received from private firms, government departments or the German Science Foundation have significant positive effects on regional patent activity.

Table A1: Overview of recent empirical studies (continued)

Authors	Data and econometric approach	Regional Units	Dependent or Outcome Variable(s), Questionnaire question(s)	(Significant) Effects
Spehl et al. (2007)	Panel data (1995-2003), Technological growth (patents) and academic staff in the neighboring regions are considered, multiple linear regression model (General-Least-Squares (GLS), FE- and RE-Estimator)	Federal State Rhine-land-Palatinate 36 regional units (Kreise)	*Dependent variables*: Real gross value added, Patents	Regional public knowledge capital as well as the regional human capital increases the real value added. However, the results indicate that both input factors do not have significant indirect effects on labor and physical capital. The academic staff in the region itself has no significant effects on patent applications, while constructing a variable including the academic staff from neighboring regions as well leads to significant positive effects on regional patent applications. This applies only for technical colleges.
Glückler and König (2011)	Case Study Ruprecht-Karls-University Heidelberg	Heidelberg University Region (Heidelberg, Mannheim and Rhein-Neckar district)	*Outcome variables*: Regional income and employment effects	Regarding direct and indirect effects, the existence of the university contributes to an income of 673 Mio. € per year and facilitates 21.600 jobs (conservative estimation).
Schubert and Kroll (2013)	Panel data (2001-2009), FE and RE-Estimators	German NUTS-III Regions	GDP per capita, Unemployment-Rate, Available income per capita, Patent-Application per capita	Compared to an average region with local academic activities, a region without such activities has an approximately 4.500 € lower GDP per capita, a 3 % higher unemployment rate and 12.5 % less patent volume. Especially the effects on the GDP per capita are regionally bounded (85 %), while the regional effects on the unemployment rate are limited (19%).

Table A2: Summary Statistics

	Number of Observations	Mean	Std. Dev.	Min	Max
Regional economic variables					
lgdp	3096	10.77384	.2548694	10.04048	11.66673
lemp	3096	-.4980849	.1449697	-.9412167	-.054104
lemp_detrended	3096	-.4883598	.1443927	-.860197	-.0472641
lhk	3096	-2.983249	.4620051	-4.16754	-1.576675
lhk_detrended	3096	-3.221792	.4775752	-4.312091	-1.909949
linvq	3096	-3.827942	.5522995	-5.910307	-1.496212
lpat	3096	-6.519584	1.424882	-11.25526	-2.295947
w_lgdp	3096	10.87333	.2253164	10.24876	11.45012
w_lemp	3096	-.4412998	.0860433	-.7334062	-.1873686
w_lemp_detrended	3096	-.4320978	.0892868	-.7239823	-.1842588
w_lhk	3096	-2.721685	.3560248	-3.796473	-1.802598
w_lhk_detrended	3096	-2.951084	.3576126	-3.955346	-2.156658
w_linvq	3096	-3.822068	.3798358	-5.172833	-2.373494
w_lpat	3096	-6.043582	1.075091	-10.14439	-3.817606
Publicly funded reserach variables - Publications					
lpubli_acad	3096	-9.725722	3.175495	-12.25371	-2.396072
lpubli_acad_detrended	3096	-9.774321	3.171512	-14.30132	-2.226343
lpubli_uni	3096	-10.08615	3.282521	-12.24644	-2.388551
lpubli_fh	3096	-6.4869	1.226142	-7.665687	-2.950004
lpubli_fh_detrended	3096	-6.279768	1.067637	-9.18298	-2.552549
lpubli_ri	3096	-8.983649	2.071075	-10.17572	-1.632857
lpubli_ri_detrended	3096	-8.849363	1.976066	-12.60853	-1.523391
lpubli_fraun	3096	-7.266902	1.225001	-8.039991	-1.552246
lpubli_fraun_detrended	3096	-7.014822	1.140555	-9.96608	-1.651817
lpubli_mp	3096	-9.019854	1.847922	-9.733763	-1.522484
w_lpubli_acad	3096	-6.687362	2.215798	-13.64	-3.995355
w_lpubli_uni	3096	-6.849181	2.528713	-13.63273	-3.996057
w_lpubli_fh	3096	-5.888524	.8708062	-9.051981	-3.471537
w_lpubli_ri	3096	-7.218412	2.263648	-11.56201	-3.298725
w_lpubli_ri_detrended	3096	-7.190224	2.222938	-11.7261	-3.569065
w_lpubli_fraun	3096	-6.603121	1.429416	-9.572889	-2.931362
w_lpubli_fraun_detrended	3096	-6.457738	1.351192	-9.180133	-3.023982
w_lpubli_mp	3096	-7.407837	2.302125	-11.12006	-3.510367
Publicly funded reserach variables - Third-Party Funds					
ltpf_acad	3096	-11.6105	5.284233	-16.84204	-2.187288
ltpf_acad_detrended	3096	-11.54762	5.163675	-23.19338	3.959904
ltpf_acad_pub	3096	-11.52825	5.040872	-16.53936	-2.146955
ltpf_acad_pub_detrended	3096	-11.41264	4.890525	-22.41577	3.743176
ltpf_uni	3096	-12.90011	5.223379	-16.75884	-2.148812
ltpf_uni_detrended	3096	-12.58231	5.056756	-23.12748	4.025797
ltpf_uni_pub	3096	-12.67869	5.009027	-16.46612	-2.120824
ltpf_uni_pub_detrended	3096	-12.27863	4.827756	-22.37583	3.783116
ltpf_fh	3096	-10.4164	4.197683	-14.31437	-2.107674
ltpf_fh_detrended	3096	-10.27101	3.987295	-19.32879	1.560877
ltpf_fh_pub	3096	-10.1969	3.83729	-13.88921	-1.731361
ltpf_fh_pub_detrended	3096	-9.924309	3.557232	-17.91157	1.113721
w_ltpf_acad	3096	-6.497861	2.252352	-18.22833	-3.698915
w_ltpf_acad_pub	3096	-6.551277	2.286766	-17.92566	-3.665244
w_ltpf_uni	3096	-7.240877	3.671981	-18.14513	-3.670681
w_ltpf_uni_detrended	3096	-7.23064	3.665677	-19.93073	-3.658841
w_ltpf_uni_pub	3096	-7.25696	3.622919	-17.85242	-3.647872
w_ltpf_uni_pub_detrended	3096	-7.227615	3.641433	-20.37873	-3.788366
w_ltpf_fh	3096	-6.415016	2.201155	-15.70067	-3.590849
w_ltpf_fh_pub	3096	-6.532606	2.178646	-15.2755	-3.424254

Notes: Zeros are replaced by 0.25 before normalization (pat, all publi- and tpf-variables). Suffix "_detrended" denotes detrended variable (see Table 2); see Table 1 for details on variable description.

Appendix A3: Econometric Modelling of the SpPVAR

The reduced-form SpPVAR model is a M-equation system (with M = 6, see Section 5) and can be written in matrix notation as (Eberle et al. 2017)

$$\mathbf{y}_t = \mu + \mathbf{A}(\mathbf{L})\mathbf{y}_{t-1} + \mathbf{H}(\mathbf{L})\mathbf{W}\mathbf{y}_{t-1} + \boldsymbol{\varepsilon}_t. \tag{9}$$

In equation (9), μ denotes region-fixed effects ($NM \times 1$ vector), the matrix $\mathbf{A}(\mathbf{L})$ contains the reduced-form coefficients that relate lagged values from *t-1* to current values *t* and ε_t denotes the reduced-form errors ($NM \times 1$ vector) with the variance-covariance matrix $\boldsymbol{\Sigma}_\varepsilon$ (Rickman 2010, Mitze et al. 2017). Following Mitze et al. (2017), the reduced-form errors have the following characteristics: $E(\boldsymbol{\varepsilon}_t) = 0$, $E(\boldsymbol{\varepsilon}_t\boldsymbol{\varepsilon}'_t) = \boldsymbol{\Sigma}_\varepsilon$ and $E(\boldsymbol{\varepsilon}_t\boldsymbol{\varepsilon}'_{t-h}) = 0$ (for $h = 1,2,\ldots$). According to LeSage and Pace (2010), ignoring spatial dependence across regions leads to inconsistent coefficient estimates. In order to account for spatial dependence and to prevent an omitted variables bias, we include spatial variables as right-hand side regressors in every equation. This is expressed by $\mathbf{H}(\mathbf{L})$ in equation (9), which is a coefficient matrix that relates spatial lags from *t-1* to current values *t* (Mitze et al. 2017).[16]

As described by Rickman (2010), the reduced-form VAR has the advantage that no initial exclusion restrictions have to be imposed, but it provides only little information on the underlying economic structure. Thus, the reduced-form VAR is extended to a structural VAR (SVAR) model. The SVAR specification is a straightforward extension of equation (9) and can be expressed as (Eberle et al. 2017)

$$\mathbf{B}\mathbf{y}_t = \mu + \mathbf{C}(\mathbf{L})\mathbf{y}_{t-1} + \mathbf{G}(\mathbf{L})\mathbf{W}\mathbf{y}_{t-1} + \mathbf{D}\mathbf{e}_t. \tag{10}$$

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[16] In the study of Mitze et al. (2017), this matrix is denoted by B_1. For the construction of the spatial weighting matrix **W**, we refer to Section 4 of this paper.

As Rickman (2010) points out, "$\mathbf{B}$ is the matrix of structural parameters for the contemporaneous variables, $\mathbf{C(L)}$ is a matrix of polynomials relating contemporaneous to lagged variables, and $\mathbf{D}$ measures the contemporaneous responses of endogenous variables to exogenous shocks" (Rickman 2010, p. 27). By premultiplying equation (10) with $\mathbf{B}^{-1}$, we obtain the reduced-form VAR model in equation (9), with $\mathbf{A}(\mathbf{L}) = \mathbf{B}^{-1}\,\mathbf{C}(\mathbf{L})$ and $\boldsymbol{\varepsilon}_{\mathrm{t}} = \mathbf{B}^{-1}\mathbf{e}_{\mathrm{t}}$ (Rickman 2010). In line with this, the spatial extension applied by Eberle et al. (2017) defines $\mathbf{G}(\mathbf{L})$ as a matrix of polynomials that relate contemporaneous to time lagged spatial regressors, with $\mathbf{H}(\mathbf{L}) = \mathbf{B}^{-1}\,\mathbf{G}(\mathbf{L})$. Straightforward, the coefficient matrix $\mathbf{C}(\mathbf{L})$ contains the direct, while $\mathbf{G}(\mathbf{L})$ contains the spatially indirect effects of shocks in $\mathbf{y}_{t-1}$ on $\mathbf{y}_t$ (Eberle et al. 2017). Similar to the study of Eberle et al. (2017), the analysis is focused on the IRFs based on the coefficient matrix $\mathbf{C(L)}$, the coefficient matrix $\mathbf{G(L)}$ is primarily used to obtain unbiased coefficients.

$\mathbf{C}(\mathbf{L})$, $\mathbf{G}(\mathbf{L})$ and $\mathbf{e}_{\mathrm{t}}$ can be calculated by estimating the reduced-form VAR in equation (9), while $\mathbf{B}$ and $\mathbf{D}$ are not known. Thus, we have to set restrictions to identify the structural parameters as well as the shocks (Rickman 2010). We follow the argumentation of Di Giacinto (2010) to use an approach that was originally proposed by Wold (1954) by assuming a recursive causal order of our endogenous variables in order to get an exactly identified specification. As Di Giacinto (2010) additionally points out, this assumption of contemporaneous exogeneity is analogous to an orthogonalization of the error terms by means of a Choleski decomposition using the variance-covariance matrix of the reduced-form residuals (Sims 1980, Hamilton 1994).

In order to illustrate the reaction of one variable to an isolated (uncorrelated) shock in another variable in our regional system, Impulse-Response Functions (IRFs) will be computed (Lütkepohl 2005). The statistical significance of the estimated IRFs is derived by generating confidence intervals using Monte Carlo (MC) simulations (Love and Zichino 2006).