Fritsch, Michael; Slavtchev, Viktor

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TECHNICAL UNIVERSITY BERGAKADEMIE FREIBERG
TECHNISCHE UNIVERSITÄT BERGAKADEMIE FREIBERG

FACULTY OF ECONOMICS AND BUSINESS ADMINISTRATION
FAKULTÄT FÜR WIRTSCHAFTSWISSENSCHAFTEN

Michael Fritsch
Viktor Slavtchev

Measuring the Efficiency of Regional Innovation Systems – An Empirical Assessment

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Addresses for correspondence:

Prof. Dr. Michael Fritsch†
Technical University of Freiberg
Faculty of Economics and Business Administration
Lessingstraße 45, D-09596 Freiberg (Germany)
Phone: ++49 / 3731 / 39 24 39
Fax: ++49 / 3731 / 39 36 90
E-mail: michael.fritsch@tu-freiberg.de

Dipl.-Volksw. Viktor Slavtchev
Technical University of Freiberg
Faculty of Economics and Business Administration
Lessingstraße 45, D-09596 Freiberg (Germany)
Phone: ++49 / 3731 / 39 20 27
Fax: ++49 / 3731 / 39 36 90
E-mail: viktor.slavtchev@tu-freiberg.de

† German Institute for Economic Research (DIW) Berlin, and Max-Planck Institute of Economics, Jena, Germany.

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Contents

Abstract

We measure the efficiency of regional innovation systems (RIS) in Germany by means of a knowledge production function. This function relates private sector Research and Development (R&D) in a region to the number of inventions that have been registered by residents of that region. Two approaches are followed. First, it is assumed that differences in the productivity of private sector R&D between regions affect the slope of the KPF, which represents the marginal productivity of R&D input. The second approach assesses regional differences within the framework of a stochastic frontier knowledge production function. This approach mainly reveals differences with regard to the intercept of the knowledge production function and, therefore, with regard to the average productivity. We compare the results of both approaches and discuss a number of critical issues such as the properties of the distribution of efficiencies, the appropriate size of RIS, and how to deal with the issue of spatial autocorrelation.

JEL-classification: O31, O18, R12
Keywords: Knowledge, innovation, spillovers, patents, regional analysis.

Zusammenfassung

„*Messung der Effizienz regionaler Innovationssysteme – eine empirische Untersuchung*“

Wir messen die Effizienz der regionalen Innovationssysteme (RIS) in Deutschland anhand einer Wissensproduktionsfunktion. Diese Funktion stellt einen Zusammenhang zwischen der Anzahl der von den Einwohnern einer Region angemeldeten Patente und der Anzahl der FuE-Beschäftigten im Privatsektor in der Region. Zwei alternative Methoden zur empirischen Berechnung der Wissensproduktionsfunktion werden vorgestellt. In einem ersten Ansatz nehmen wir an, dass sich Unterschiede der Produktivität der FuE-Beschäftigten in der Steigung der Wissensproduktionsfunktion und somit in der Grenzproduktivität der FuE-Aktivitäten niederschlagen. Ein zweiter Ansatz bestimmte die Durchschnittsproduktivität der FuE-Beschäftigten mittels einer stochastischen Frontier-Wissensproduktionsfunktion. Wir vergleichen die Resultate beider Ansätze und diskutieren kritische Fragen hinsichtlich der Verteilungscharakteristika der technischen Effizienz von Regionen, der adäquaten Größe regionaler Innovationssysteme sowie der Präsenz und der Effekte räumlicher Interdependenzen zwischen den Regionen (räumlicher Autokorrelation).

JEL-Klassifikation: O31, O18, R12
Schlagworte: Wissen, Innovation, Externalitäten, Patente, regionale Analyse.

1. Introduction

Innovation activity is not evenly distributed over space but tends to be clustered in certain regions (Enright, 2003; Feldman, 1994; Porter, 1998; Moreno, Paci and Usai, 2005). One main reason for this is that, obviously, some locations are better suited for innovative activity than others. It has frequently been speculated that regional innovation systems (RIS) may differ considerably with regard to their 'quality' and 'efficiency'. For example, a number of authors hypothesize that large cities provide better conditions for innovation than remote and rural areas (see Fritsch, 2000, for an overview). However, the available empirical evidence for this and other hypotheses is not at all convincing because it is mainly based on case studies for single regions and not on a systematic interregional comparison. We still know only very little about the regional conditions that are conducive or unfavorable for innovation activity. Moreover, it is not clear how to measure the quality of regional innovation processes.

This paper elaborates on different measures for the efficiency of RIS. We first describe what we mean by efficiency of RIS (section 2) and then introduce two measures for RIS efficiency, which are both based on the concept of a knowledge production function (section 3). Section 4 gives an overview of the regional distribution of private sector R&D input and the respective output. The two measures of the efficiency of RIS are presented and compared in section 5. Finally, we draw conclusions for further research (section 6).

2. What does efficiency of regional innovation systems mean?

The term efficiency is used in a variety of different ways. Our understanding of the efficiency of RIS corresponds to the concept of technical efficiency as introduced by Farrell (1957). Technical efficiency is defined as the generation of maximum output from a given amount of resources. A firm is regarded technically inefficient if it fails to obtain the maximum possible output. Another important type of efficiency, allocative efficiency, pertains to the optimal choice of inputs.[1] Reasons for technical inefficiency can be manifold and comprise all kinds

[1] A firm is allocatively efficient if its input combination is optimal given input prices and marginal productivities. A firm can be allocatively efficient, but at the same time technically inefficient, if it chooses an

of ‘mismanagement–like’ inappropriate types of work organization and the use of technology, bottlenecks with regard to certain inputs as well as X-inefficiency as exposed by Leibenstein’s (1966) seminal work. Thus, inefficiency is a failure to meet the best practice of production process.

To apply the concept of technical efficiency to innovation processes may be regarded problematic for a number of reasons. First, innovation processes are stochastic in character, thus their exact results are undetermined. Second, due to the unique and individual character of every innovation, not only the results of innovation activity but also the best or appropriate ways for achieving these results are unknown. Even if an appropriate result is attained by a certain procedure, the uniqueness of each innovation implies that one can never know if this procedure will also be appropriate if applied to a new problem. Due to the variety of possible results and procedures, innovation processes may not be comparable. It could, therefore, be regarded as problematic to term a certain process or result ‘inefficient’ based on a comparison that may be regarded totally inappropriate. However, inventions and innovations can be measured and counted even if each one is unique. In combination with information from the input to the innovation process, these data can be used to relate innovative input and output in the sense of a macroeconomic relationship. In this paper we will use the concept of a knowledge production function (KPF) and apply the basic concept of technical efficiency analysis for assessing the quality of regional innovation systems. In particular, we will use the relationship between the input and the output of the regional innovation activity for assessing the efficiency of RIS.

The reasons for high efficiency of RIS as measured by some input-output relationships can be manifold. To begin, innovation processes may be well organized and managed with the right decisions being made at the right time. Other factors influencing the efficiency of RIS may be related to the regional and the sectoral environment of the innovating units. Main determinants of RIS on the regional level may be the size and richness of regional input markets, particularly the labor market, and the availability of high-quality services. All kinds

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optimal input combination but does not attain the highest possible isoquant of its production function (Farrell, 1957).

of agglomeration advantages such as spatial clustering of firms working in the same technological field may fuel innovation processes significantly.[2] A rather important input may be the presence of a research university and the knowledge spillover that it produces.[3] There are also 'soft' location factors such as informal networks and the 'milieu' which may have considerable impact on the efficiency of innovation activity (Aydalot, 1986; Crevoisier and Maillat, 1991). Since innovation processes are characterized by a pronounced division of labor which is, to a considerable degree, concentrated in the region, the intensity and the quality of this labor division should affect their efficiency (Fritsch, 2004).[4]

3. Measuring efficiency of RIS

3.1 Basic idea

Our measures of efficiency are based on a regional knowledge production function that describes the relationship between innovation input and innovation output (Griliches, 1979; Jaffe, 1989). The basic hypothesis behind the knowledge production function is that inventions do not fall completely 'from heaven' but result predominantly from systematic R&D efforts, i.e.,

(1) *R&D output = f (R&D input).*

Adopting the Cobb-Douglas form of a production function, the basic relationship can be written as

(2) $R\&D\ output = a\ (R\&D\ input)^{b}$,

with the term *a* representing a constant factor and *b* giving the elasticity by which R&D output varies in relation to the input to the R&D process. Taking the natural logarithms

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[2] See Porter (1998); Baptista and Swann (1998); Oerlemans, Meeus and Boekema (2001); Enright (2003).

[3] See Acs, Audretsch and Feldman (1992); Anselin, Varga and Acs (1997, 2000); Varga (2000); Fritsch and Slavtchev (2005).

[4] For an overview of the factors which may influence the efficiency of RIS see Fritsch and Slavtchev (2006).

on both sides and adding an index *r* for the region as well as a stochastic error term (ε) we get

(3) $ln\ (R\&D\ output)_r = ln\ a + b * ln\ (R\&D\ input)_r + \varepsilon_r$.

This equation can be estimated by applying standard regression techniques.

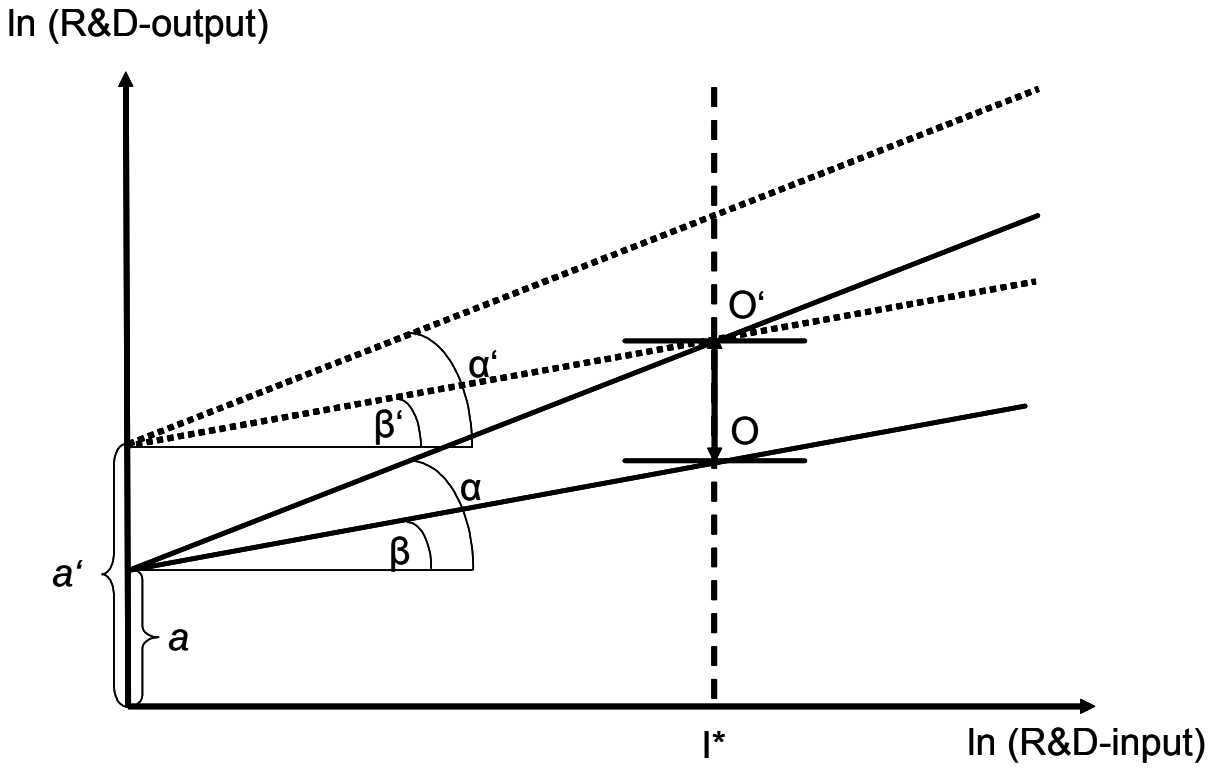


Figure 1: Efficiency in the relationship between R&D input and output

Knowledge production functions for regions may differ with respect to their slope as well as their constant term. Accordingly, differences in the relationship between R&D input and output between regions – such as that between P and P’ in figure 1 – may be caused by a different slopes (tan α vs. tan β in figure 1) as well as by differences in the constant term (a vs. a’). The slope of the knowledge production function gives the output elasticity of R&D input and may be interpreted as a measure of the marginal productivity of the input to the innovation process. If, for example, the quality of inputs to the R&D process is improving or if spillovers from the R&D activities of other actors in the region become more pronounced, the input elasticity of R&D output should increase, i.e., the knowledge production function

should have a steeper slope (e.g., tan α instead of tan β in figure 1). Differences between regions with regard to the constant term of the knowledge production function indicate higher innovative output at any level of input. If knowledge production functions have the same slope but differ with regard to the constant term this means that regions have different average productivity but that their marginal productivity is identical. Differences in the constant term of the knowledge production function may be explained by all kinds of characteristics of RIS that influence average productivity of R&D input but do not necessarily affect marginal productivity. An illustrative example of such differences that only pertain to average productivity of R&D input and not to marginal productivity could be innovations that are not entirely based on current R&D but also on the existing stock of 'old' knowledge. Moreover, the presence of informal networks and 'milieux' may mainly affect average productivity. Since, in practice, we are only able to assess the relevant knowledge stock rather incompletely, differences with regard to the constant term of the knowledge production function may also reflect a misspecification or incomplete measurement of the input variable.

3.2 Deterministic and stochastic knowledge production function

There are two approaches of estimating a knowledge production function. Estimating an ordinary regression implies a deterministic approach. In such a deterministic approach the largest estimated value of the slope or of the constant term of the knowledge production function is taken as a benchmark value for assessing the efficiency of the other regions. An estimate of the efficiency E_r of the region r is then calculated as

(4) $$E_r = \left(\hat{a}_r / \max \hat{a}_r\right) * 100 \ [\%]$$

if efficiency is assessed by the constant term of the knowledge production function or

(5) $$E_r = \left(\hat{\beta}_r / \max \hat{\beta}_r\right) * 100 \ [\%]$$

for efficiency as measured by the function's slope. According to this approach, at least one region will meet the benchmark value and the remaining regions will have efficiency values between 0 and 100 percent of this benchmark value. The approach is called 'deterministic' because all deviations from the maximum values are only due to inefficiency.

In contrast to this deterministic approach, a stochastic knowledge production function is based on the assumption that the input-output relationship is also subject to erratic influences

(Aigner, Lovell and Schmidt, 1977; Meeusen and van den Broeck, 1977; Greene, 1997). In a stochastic approach efficiency is identified by decomposing the error term of the frontier knowledge production function into two components, i.e., $\varepsilon_r = u_r - v_r$, i.e.,

(6) $ln\ (R\&D\ output)_r = ln\ a + b * ln\ (R\&D\ input)_r + u_r - v_r$.

The component that is reflecting the random disturbances (u_r) can be assumed to follow a symmetric normal distribution. The second component (v_r) is an asymmetrically distributed, non-negative random term that represents the technical inefficiency. Thus, the technical efficiency of the *r*-th region can be calculated as e^{-v_r}. Measuring the efficiency by means of a stochastic frontier knowledge production function has the advantage that extreme outliers of highly efficient regions or data errors do not automatically serve as an efficiency benchmark. However, in order to separate the impact of technical inefficiency from the general stochastic effects, an *a priori* assumption about the distribution of technical inefficiency is required. Since the factual efficiency of a region cannot exceed the maximum, the distribution must be truncated at this maximum. The usual hypothesis in this respect is that most regions cluster near the efficiency frontier and that their frequency decreases with rising inefficiency. Such a distribution of the inefficiency term v_r is negatively skewed and can be described as a truncated normal or a log-normal distribution. A positively skewed distribution of the inefficiency terms is not consistent with the underlying assumptions and no stochastic function can be estimated if the distribution of the residuals is not negatively skewed.

While a deterministic knowledge production function can be taken for assessing differences with regard to the slope as well as the constant term of the knowledge production function the results of the stochastic frontier approach reflect differences in the constant term only. In our analysis, we use the deterministic approach for estimating differences in the marginal productivity of R&D input as reflected by the slope of the function. The stochastic frontier approach is applied for assessing differences in the constant term which indicates average productivity.

3.3 Specification of the knowledge production function

To estimate a knowledge production function, we use the number of disclosed patent applications as an output variable of the regional innovation processes. The information for the regional patent applications is available on a yearly basis for the period of 1995 to 2000. When relating knowledge input to innovation output we have to assume that there is a time lag for two reasons. Firstly, R&D activity requires time for attaining a patentable result. Secondly, patent applications are published only about twelve to eighteen months after submission. This is the time necessary to verify whether an application fulfils the basic preconditions for being granted a patent or to complete the patent document (Greif and Schmiedl, 2002). Eighteen month after submission a patent application has to be disclosed (Hinze and Schmoch, 2004). In our data, we found the best statistical fit for the knowledge production function when using a three year lag, i.e., when relating the input of year t-3 to innovation output of year t (Fritsch and Slavtchev, 2005).[5] Since reliable data on R&D employment in East Germany is only available for the years 1996 onwards, a time lag of three years would lead to only two observations per region for estimating the region-specific effect. In order to have more observations available, we reduce the time lag between R&D input and the patent application to a period of one year. This appears justified because there are no great fluctuations of both, innovation input and innovation output, over the years. Thus, differences between an estimated knowledge production function with a time lag of one year and with a time lag of three years are negligible.

In an analysis of the knowledge sources of innovation for West German districts[6] (*Kreise*) with the number of patent applications as the dependent variable, we found a dominant effect for the number of private sector R&D employees in the region. Further

[5] Acs et al. (2002) report that US innovation records in 1982 result from inventions made 4.3 years ago. Fischer and Varga (2003) use a two year lag between R&D efforts and patent counts in Austria in 1993. Ronde and Hussler (2005) link the innovative output, the number of patents between 1997 and 2000, to R&D efforts in 1997.

[6] The German districts (*Kreise*) coincide with the NUTS-3 regional classification. The Nomenclature of Territorial Units for Statistics (NUTS) was established by Eurostat in order to provide a single uniform breakdown of territorial units for the preparation of regional statistics for the European Union. For the definition of NUTS regions see http://europa.eu.int/comm/eurostat/ramon/nuts/introduction_regions_en.html.

knowledge sources that had a significant effect were the number of R&D employees in adjacent regions, which indicates the presence of spatial knowledge spillovers, as well as the amount of external research funds attracted by public research institutions (Fritsch and Slavtchev, 2005). In order to assess the efficiency of RIS, we only include regional private sector R&D employment as an explanatory variable into the knowledge production function and omit other input variables. This is done for three reasons. First, if the omitted variables are included the resulting increase of the R^2 value is rather small. Second, since we have only four observations per region there are only limited degrees of freedom left to include more explanatory variables. Third, knowledge spillovers from adjacent regions as well as the presence of public research institutions can be regarded as a source of relatively high efficiency of RIS and should, therefore, not be used for measuring it. We judge the quality of RIS by the efficiency of private R&D activity that is regarded decisive for the performance of the regional economy.

Our dependent variable, the number of patents, has the form of a non-negative integer. Assuming that the number of patents is generated by a Poisson-like process, the Poisson-regression analysis may be applied. However, we used the negative-binomial (negbin) regression because it is based on somewhat more general assumptions than the Poisson regression.[7]

3.4 Data and measurement issues

Information on the yearly number of disclosed patent applications, our indicator for innovation output, is available for the 1995 to 2000 period from Greif and Schmiedl (2002). A patent application indicates that an invention has been made which extends the existing knowledge pool. However, using patents as an indicator for new knowledge underestimates the output of activities in basic research where the results cannot be patented (Acs, Anselin and Varga, 2002; Griliches, 1990). A patent is assigned to the district in which the inventor

[7] Negative binomial regression allows for a greater variance of observations than is assumed for a Poisson process. For a more detailed description of these estimation methods see Greene (2003, 740-745). Note that we find at least one patent per year for each district in our data; thus, the problem of having "too many zero values" does not apply.

has his main residence. If a patent has more than one inventor, the count is divided by the number of the inventors involved and each inventor is registered with the respective share of that patent. Therefore, in event of the inventors being located in different regions, the number of patents per district may, therefore, not always be a whole number. To adjust the information on the number of patents to the assumptions of the negative binomial estimation model that we apply for assessing the efficiency of RIS, these numbers have been rounded up. The number of R&D employment in the private sector stems from the establishment file of the German Social Insurance Statistics (*Statistik der sozialversicherungspflichtig Beschäftigten*) as described and documented by Fritsch & Brixy (2004). Employees are classified as working in R&D if they have a tertiary degree in engineering or in natural sciences.

All these data are available on a yearly basis at the level of the 439 German districts. Performing the analysis at the level of districts would have the advantage that districts provide a relatively fine-grained spatial pattern. The disadvantage of using districts is that they may be comprised of only a city without the surrounding but closely related area; thus, they may be regarded as too small for representing RIS. An alternative spatial pattern to be used for the analysis is given by the 97 German planning regions (*Raumordnungsregionen*). The advantage of using planning regions instead of districts is that these regions include at least one core city as well as its surroundings. The spatial concept of planning regions focuses on commuter distances; therefore, they account for travel to work areas and provide a better representation of functional spatial economic entities than districts.[8] We present results for both levels of spatial aggregation.

4. The regional distribution of patents and private sector R&D

The number of private sector R&D employees as well as the number of innovations that have been registered for patenting is considerably concentrated in space (table 1 and figure 2). The

[8] For this definition of the planning regions, see Federal Office for Building and Regional Planning (*Bundesamt für Bauwesen und Raumordnung, BBR*) (2003).

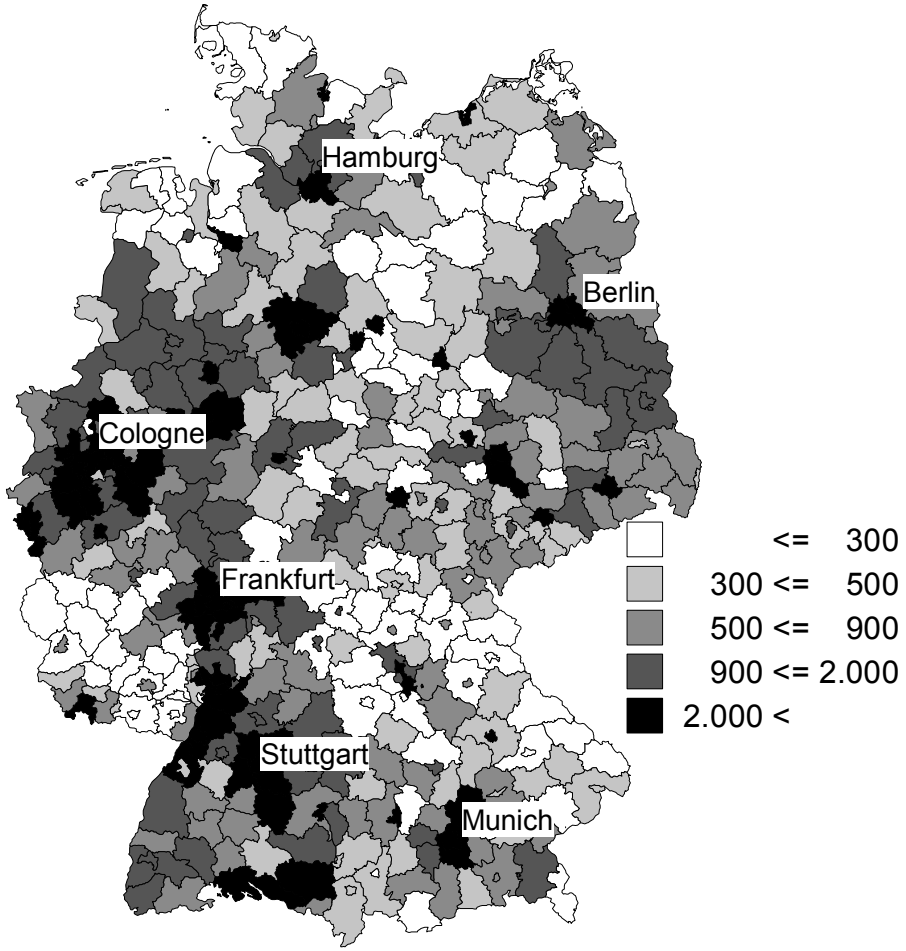
large differences between the median and the mean values indicate that the distribution of these variables is rather skewed.

Table 1: Descriptive statistics for the distribution of the number of patents (1997-2000) and the number of R&D employees (1996-1999) in German districts (average yearly values)

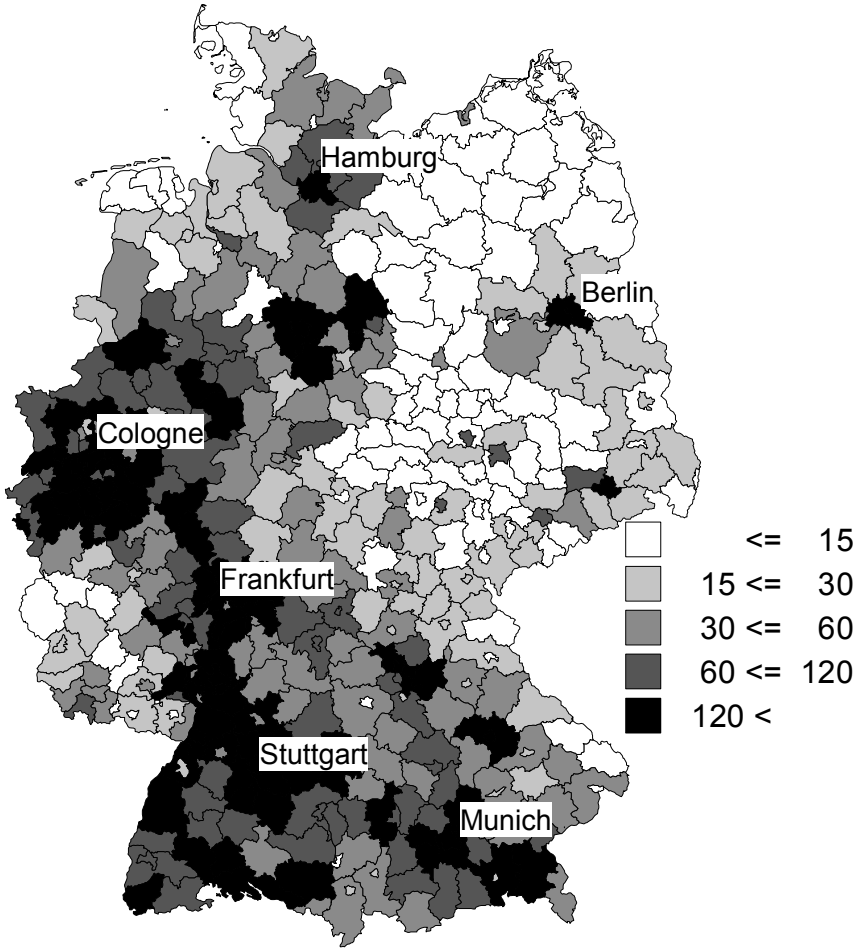
Variable	Mean	Standard. Deviation	Minimum	Maximum	Median	S-Gini inequality measure
No. of patents	83.78	122.48	1.15	1,275.54	44.83	0.58
No. of private sector R&D employees	1425.28	2918.86	35.50	33,394.75	612.75	0.62

There was no German district without private sector R&D employment in the 1996 to 1999 period. However, the number of private sector R&D employees varies strongly between 35 persons in regions on the northern German border and more than 30,000 in the city of Munich. Not surprisingly, the number of private sector R&D employees is relatively high in densely populated areas such as the cities of Munich, Stuttgart, Frankfurt, Cologne, Hamburg, Berlin, and their surroundings (figure 2). It tends to be relatively small in peripheral and rural regions. Comparing the spatial distribution of the number of patents with the number of R&D employees reveals some correspondence as well as considerable differences. At the level of the German districts, the Pearson correlation coefficient between the number of patents and the number of private sector R&D employees is 0.81 indicating that regions with a high number of R&D employees also tend to have a relatively high number of patents.[9] However, the relation between innovation input and output differs considerably between regions.

[9] At the level of the planning regions the correlation between the number of patents and the number of private sector R&D employees is above 0.92.



Private sector R&D employment 1996-1999 (average yearly values)



Number of patents 1997-2000 (average yearly values)

Figure 2: Spatial distribution of innovative input and output in German districts

This is particularly obvious for East Germany, the former German Democratic Republic, when the Berlin region is disregarded. While the share of private sector R&D employees in East Germany is about 20 percent of all R&D employees this part of the country accounts for only 9 percent of the patents. Particularly low number of patents can be found in rural Mecklenburg-Western Pomerania, the regions north of Berlin (about 15 patents per year). Similar to the distribution of R&D employees, the number of patents tends to be relatively high in areas such as Munich, Stuttgart, Cologne, Frankfurt, Hamburg, and their surroundings (figure 2). These five cities account for 2,925 patents per year which is equivalent to 7.95 percent of all German patents. There is a remarkable concentration of the number of patents in southwest Germany.[10] The Gini spatial inequality measure for the number of patents and the number of private sector R&D employment indicate that patents are somewhat more evenly spread in space than R&D employment (table 1). The difference between these two values is, however, not very large.

5. Results for efficiency measures

The results of a deterministic knowledge production function at the district level and at the level of the planning regions (table 2) show a strong impact of the number of private sector R&D employees on the number of patents. At the level of the districts, the production elasticity of private sector R&D employment is 0.689 indicating that an increase of R&D employment by one percent leads to an increase in the number of patents of nearly 0.69 percent. The fact that this input-output relationship is considerably stronger at the level of planning regions, which comprise several districts, indicates the presence of knowledge spillovers between adjacent districts. The pseudo R^2-statistics suggests that the number of private sector R&D employees is well suited for describing the greatest part of the variance of the dependent variable for both spatial categories, districts and planning regions. According to the constant term of the model, there are only 0.66 patents on the level of the districts and 0.17 patents on the level of the planning regions that cannot be attributed to private sector R&D effort as measured by R&D employment.

[10] For a detailed description of the regional distribution of innovative input and output see Greif and Schmiedl (2002), Fritsch and Slavtchev (2005), Deyle and Grupp (2005).

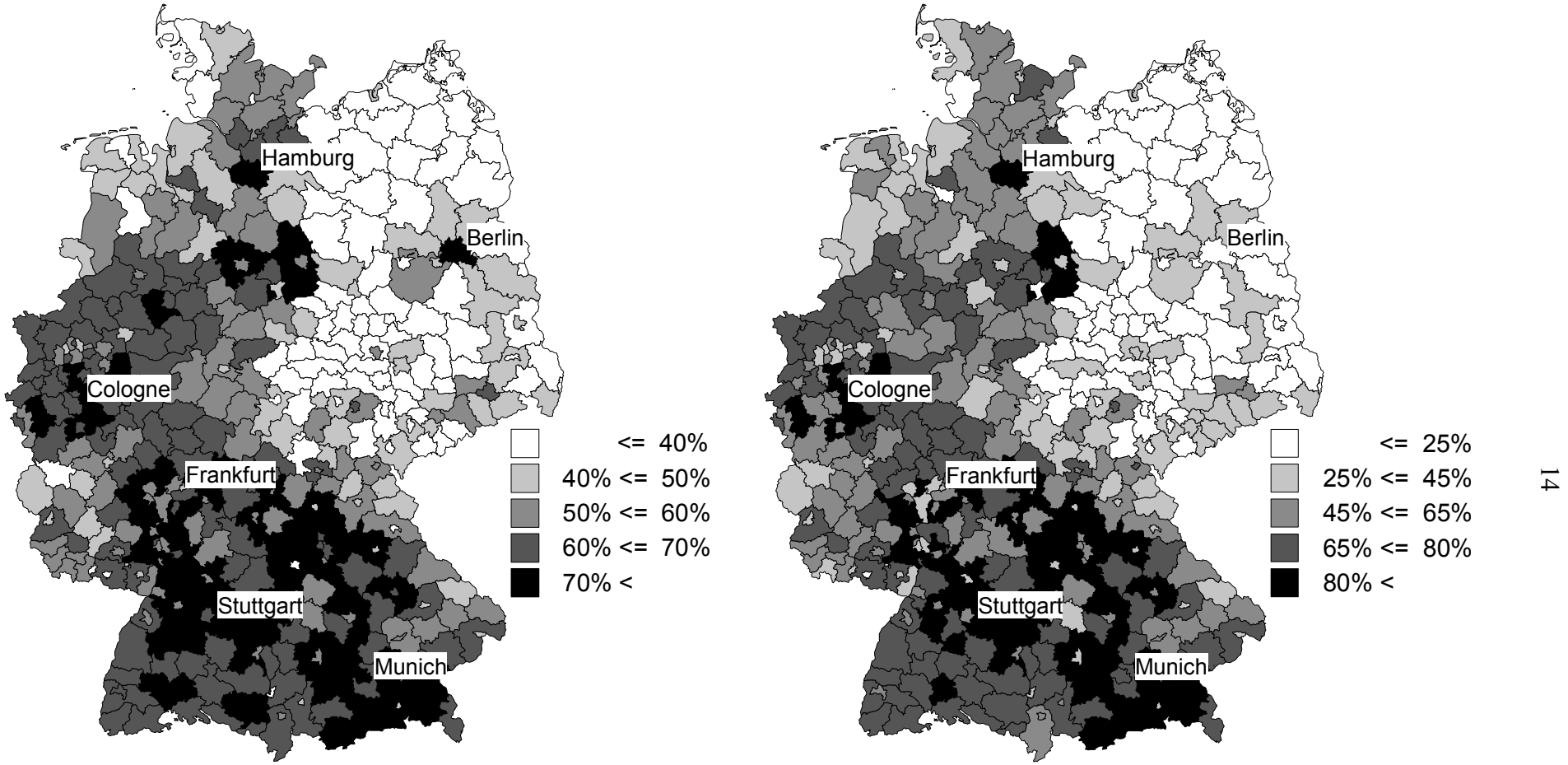
Table 2: The deterministic knowledge production function [a]

	Regional number of patents	
	Districts	Planning regions
Private sector R&D employees (ln)	0.689**	0.885**
	(0.037)	(0.051)
Intercept	-0.421**	-1.773**
	(0.262)	(0.441)
N	1,756	388
Alpha	0.635	0.365
	(0.038)	(0.045)
Wald χ^2 (1)	346.07**	306.46**
Pseudo R^{2adj}	0.933	0.916

[a] Results of robust negbin regression. Robust standard error in parentheses. ** statistically significant at the 1% level.

As indicated by figure 3 there are considerable differences of technical efficiency at the level of the German districts. The relatively low values for technical efficiency in East Germany show that the innovation system in this part of the country is rather inefficient. The Berlin region, with a relatively high RIS efficiency, is an exception in the East German innovation landscape. Many of the regions with a relatively high level of technical efficiency are located in the southern and in the western parts of the country. Generally, the values for the technical efficiency of RIS tend to be higher in larger, densely populated cities such as Munich, Stuttgart, Cologne, Frankfurt, Hamburg, and their surroundings. Location in border regions seems to be unfavorable.

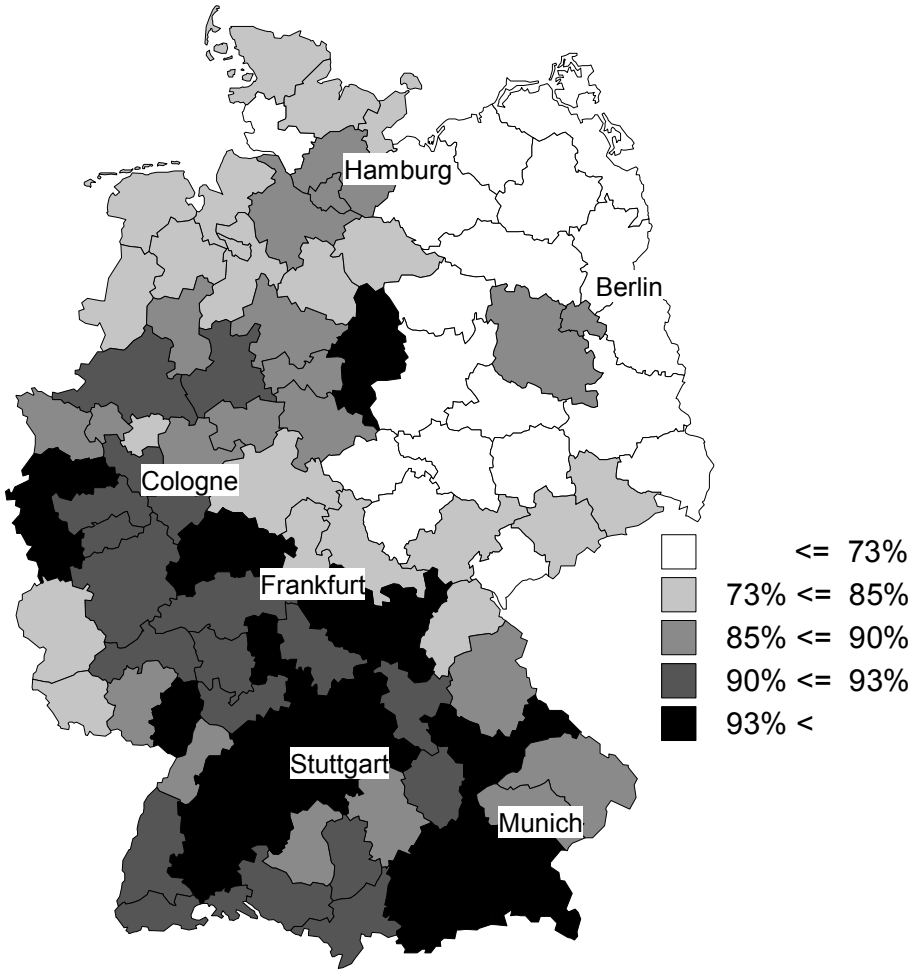
Figure 3 clearly shows that adjacent districts quite often fall into the same efficiency category. This may be regarded as an indication that regional innovation systems comprise larger spatial units than districts. It is also quite remarkable that some of the smaller cities have relatively low efficiency values. One main reason for this phenomenon is that a number of R&D employees that work in the center reside in a surrounding district taking advantage of a lower cost of living (e.g., real estate prices) and a higher quality of the environment. In these cases, the innovative output of the city center is underestimated since patents are assigned to the residence of the inventor (Deyle and Grupp, 2005). In order to avoid such distortions and to analyze the RIS comprehensively, we chose German planning regions as the spatial units for the analysis. The advantage of using planning regions instead of districts is that by



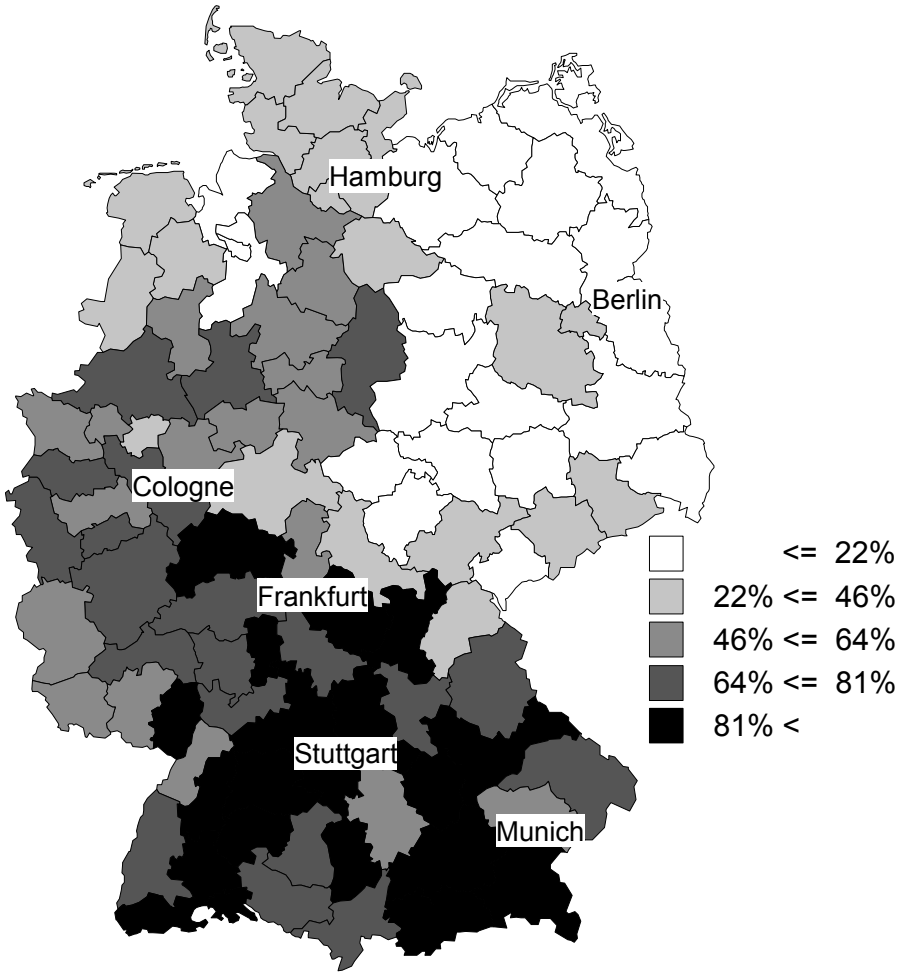
Deterministic knowledge production function

Stochastic frontier knowledge production function

Figure 3: Technical efficiency of German RIS as assessed by means of a deterministic knowledge production function at the district level (in percent of the most efficient region)



Deterministic knowledge production function



Stochastic frontier knowledge production function

Figure 4: The distribution of technical efficiency of RIS in German planning regions (in percent of the most efficient region)

including at least one core city as well as its surroundings they provide a better representation of functional spatial economic entities than districts. For historical reasons, the cities of Berlin, Hamburg, and Bremen are defined as planning regions even though they are not functional economic units. In order to create functional units, these cities have been merged with adjacent planning regions for the analysis (cf. figure 4).[11]

There is a wide dispersion of technical efficiency of RIS among the planning regions as determined by the slope of a deterministic knowledge production function that reflects the marginal productivity of R&D input (figure 5 and table 3). The regions with the highest efficiency values are located in the south of Germany, particularly clustered around Munich and Stuttgart. The innovation systems in regions in the north and the east of the country tend to be considerably less efficient. The lowest efficiency estimates are found for regions in the northeast such as "Mecklenburgische Seenplatte", "Vorpommern" and "Altmark". The least efficient region attains only about 53 percent of the productivity of the most efficient region.

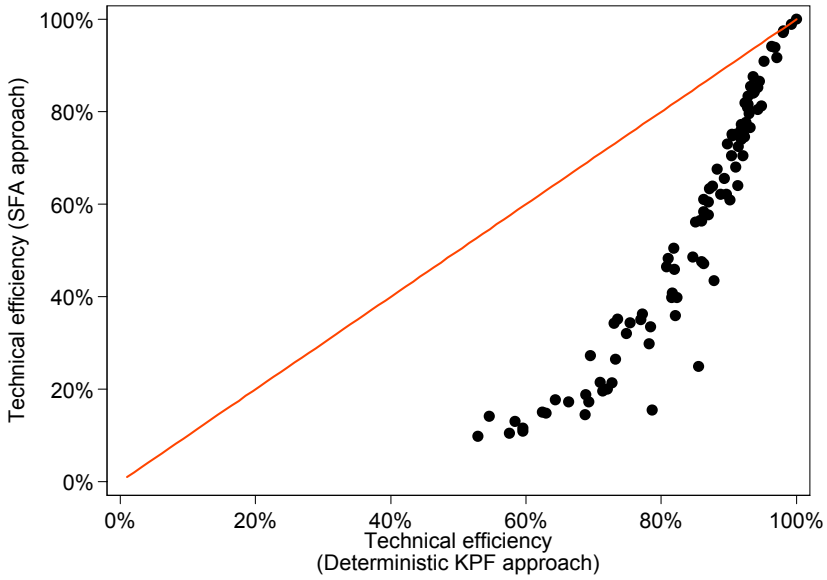


Figure 5: Technical efficiency of RIS in German planning regions assessed with a deterministic and with a stochastic frontier knowledge production function

[11] Berlin was merged with the region Havelland-Flaeming, Hamburg with the region Schleswig-Holstein South, Bremen with Bremerhaven and with the region Bremen-Umland.

Table 3: Descriptive statistics for the distribution of technical efficiency in German planning regions (in percent of the most efficient region)

Variable	Mean	Standard Deviation	Minimum	Maximum	Median	Pearson's Correlation
Technical efficiency (deterministic knowledge production function)	83.72	11.48	52.94	100	87.01	0.94
Technical efficiency (stochastic knowledge production function)	55.12	26.87	9.77	100	60.49	

The efficiency levels estimated by means of a stochastic frontier function, which reflect the average productivity of R&D input, show an even wider spread with the less efficient region attaining only 9.8 percent of the highest value (table 3 and figure 5). As compared to the deterministic knowledge production function, the stochastic frontier approach leads to a much more distinguished assessment of RIS efficiency, particularly among the less efficient regions. The greater dispersion of efficiency estimates derived on the basis of a stochastic frontier approach indicates that innovation systems differ more with respect to their average productivity than by marginal productivity of R&D input. However, the spatial pattern of the two efficiency distributions is very much alike (figure 4). The Pearson's correlation coefficient between the efficiency values estimated by the two approaches is 0.94.

In order to assess the presence and importance of spatial autocorrelation we applied a Moran's *I* test.[12] Under the null hypothesis of no spatial autocorrelation the expected value for Moran's *I* was estimated to be E(*I*)=-0.011. Since the computed value for Moran's *I* is significantly larger than its expected value there is positive spatial autocorrelation between the planning regions with respect to the technical efficiency of their innovation systems. [13] This

[12] Geary's *c* (Geary, 1954) and Getis' and Ord's *G* (Getis and Ord, 1992) provide two alternative measures of spatial autocorrelation. However, since Geary's *c* and Getis' and Ord's *G* do not capture for some aspects of spatial association, the Moran's *I* was chosen here, thus being the most appropriate index for the purpose of our investigation approach.

[13] $I = 0.683$ and $sd(I) = 0.065$ in the case of the deterministic knowledge production function, $I = 0.713$ and $sd(I) = 0.066$ in the case of the stochastic frontier knowledge production function.

means that regions with similar efficiency levels are clustered in space.[14] However, since the global Moran's *I* indicates the presence of spatial autocorrelation in general, it is not appropriate to assess the exact nature of spatial association at the local level of individual regions (Anselin, 1995). Four different types of spatial relationship between the technical efficiency in a particular region and their neighboring regions may exist: low-low, low-high, high-low, and high-high. In order to identify the different types of spatial clusters, the Moran scatter plot was applied (figure 6). The Moran scatter plot shows the relationship between a regions' standardized value of technical efficiency and the spatially lagged values. The slope of the line in figure 6 is equal to the global Moran's *I* that is obtained by regressing the standardized spatially lagged values on the standardized values of technical efficiency.

Clusters of planning regions with high values of technical efficiency are located in the upper right quadrant of figure 6. The respective regions are all located in the south or in the center of the country. None of the planning regions in the north or in the east of Germany fall into this category (figure 7). Regions with relatively low values for technical efficiency of their innovation system are found in the lower left quadrant of figure 6. These regions are entirely located in the north and the east (figure 7).[15] Regions with relatively weak values of technical efficiency but with relatively high efficiency values in adjacent regions can be found in the lower right and in the upper left quadrant, respectively. Not surprisingly, such regions are located predominantly in the center of the country separating the west from the east as well as the south from the north. The distribution of the different types of regions indicates that the German innovation system is spatially divided into a relatively efficient part in the southwest of the country and a part in the northeast where innovation activity is far less productive (figure 7).

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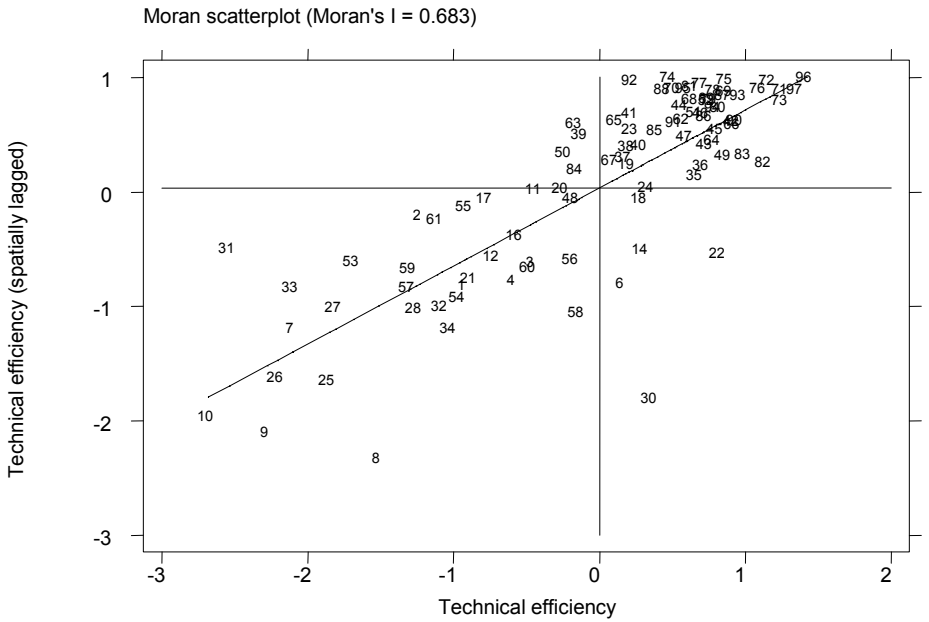
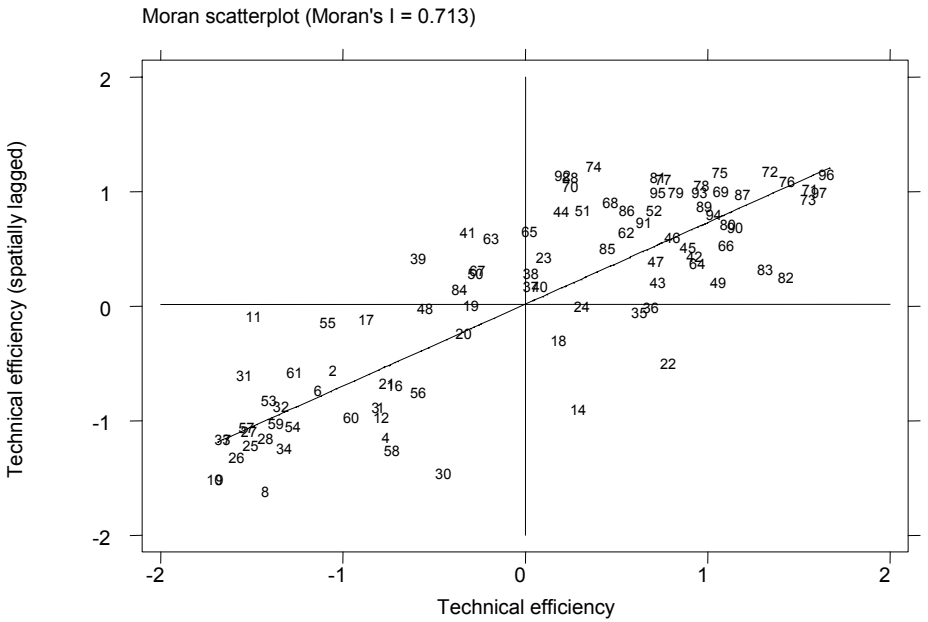
[14] A Moran's *I* smaller than its expected value would indicate that regions with relatively high and with relatively low efficiency are found in spatially contiguous locations.

[15] The local Moran's *I* (for particular location) was statistically significant at least at the five percent level for about half of the regions under investigation. It was not significant for regions in the lower right quadrant, the upper left quadrant as well as for regions close to the zero values in figure 6.



Deterministic KPF approach



Stochastic frontier KPF approach

Figure 6: Moran scatter plot of the technical efficiency of the German planning regions (numbers in the plot indicate the number of the respective planning region, not rank)

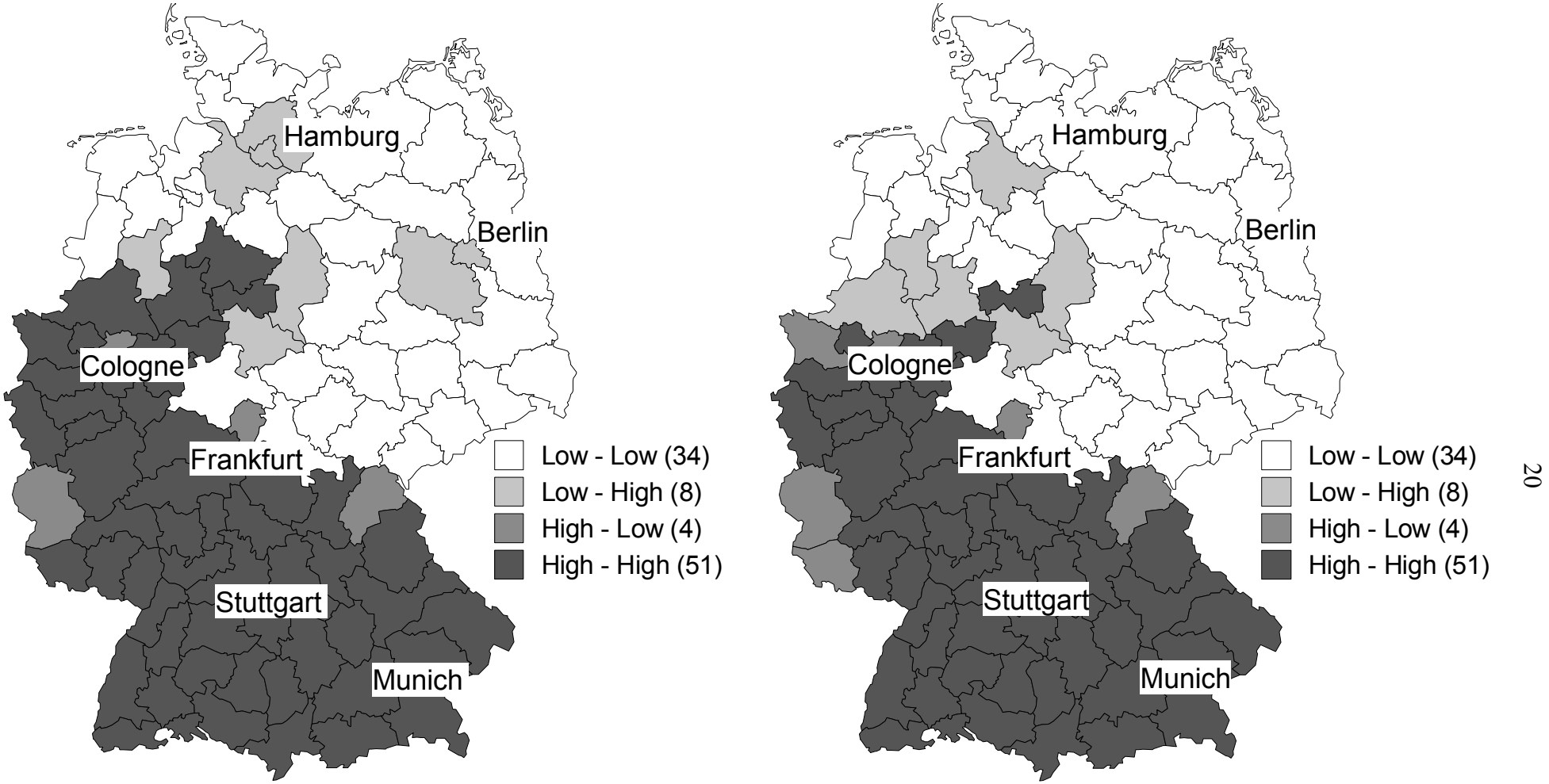


Figure 7: Moran scatter plot map of the technical efficiency of the German Planning Regions

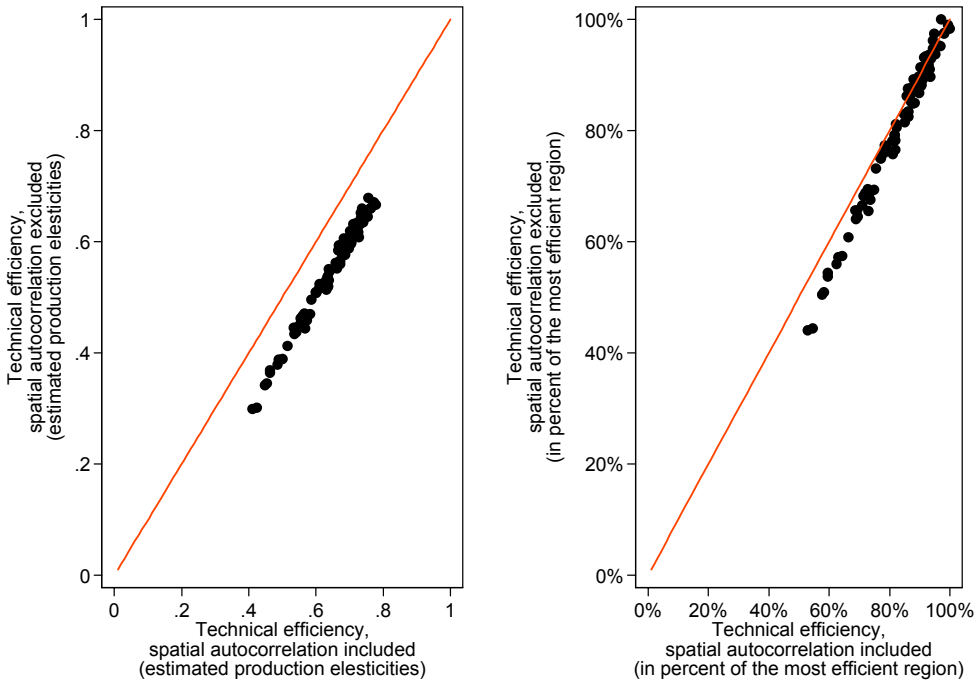


Figure 8: Technical efficiency of RIS with and without accounting for spatial autocorrelation (deterministic knowledge production function at the level of planning regions)

Table 4: Technical efficiency of RIS with and without accounting for spatial autocorrelation (deterministic knowledge production function on the level of planning regions)[a]

	Differences between estimated production elasticities without and with accounting for spatial autocorrelation (ln)
Production elasticities (deterministic KPF) (ln)	-0.191**
	(2.984)
Intercept	-2.4034**
	(75.09)
N	93
$R^{2adj.}$	0.06
F value	8.91

[a] Heteroskedasticity robust (Huber-White) OLS estimator; t-values in parentheses. ** statistically significant at the 1% level.

We have argued that spatial knowledge spillovers between adjacent regions should be neglected in assessing the efficiency of RIS because such neighborhood effects may be regarded as a determinant of the efficiency (cf. section 3.3). Moreover, the ability to benefit

from knowledge spillovers from adjacent regions depends considerably on the regions own knowledge base as well as on the region's proximity to the efficiency frontier. In order to test for the effect of spatial autocorrelation on our results we included the mean residual of the adjacent regions into our models (for detailed discussion see Anselin, 1988, 1990). A comparison of the efficiency estimates with and without such an account for spatial autocorrelation shows that production elasticities of regional R&D input are always lower if spatial autocorrelation is accounted for in the empirical model (figure 8). However, the effect of spatial autocorrelation is not very large: after control for spatial autocorrelation the estimated efficiency values are about 6 percent lower. The comparison of the two types of models suggests that the differences are particularly pronounced for low-efficiency regions. This is confirmed in a regression with the difference of the production elasticity, with and without spatial autocorrelation, as the dependent variable and the production elasticity as independent variable (table 4). The results clearly show that neighborhood effects are considerably more pronounced for regions with a relatively low efficiency of their innovation system.

6. Summary and outlook

The objective of this paper was to provide and to test appropriate measures for the technical efficiency of regional innovation systems in Germany. We measure the efficiency of regional innovation systems by means of a knowledge production function. This function relates private sector R&D effort in a region to the number of inventions that have been registered by residents of that region. Technical efficiency is defined as the generation of maximum output from a given amount of resources. A region is regarded technically inefficient if it fails to obtain the maximum possible output from its inputs. Two approaches have been followed. First, it is assumed that differences between regions affect marginal productivity of the private sector R&D as given by the slope of the knowledge production function. The second approach assesses regional differences with regard to the average productivity of R&D input in a region.

The two approaches for assessing the efficiency of RIS have both led to quite comparable results. Particularly the spatial distribution of efficiency estimates has been quite similar.

Since the districts are found to be too small for an adequate measurement of RIS we performed the main part of the analysis at the level of planning regions. There are pronounced differences in the technical efficiency of RIS. We found that regions in western and in the southern parts of Germany perform relatively well while regions in eastern Germany fall far behind. Generally, high levels of efficiency of the innovation system are attained in high-density areas while rural regions and regions in the periphery tend to be characterized by low efficiency of their RIS. Based on the Moran's *I* statistics we found strong evidence for spatial interdependences between regions. Moreover, there are pronounced tendencies for spatial clustering of regions with about the same level of technical efficiency.

The methods for assessing the efficiency of RIS which were developed here are promising. The results are rather robust and have a high degree of plausibility. Based on our results, the question arises what actually determines the differences in the efficiency of regional innovation system. In this context, variables that can be directly controlled by policy are of particular interest. Moreover, the extent to which innovative performance is affected by different kinds of externalities (i.e., specialization economies, diversity, and local competition) can be evaluated. This type of analysis is reported elsewhere (Fritsch & Slavtchev, 2006).

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Appendix

Table A1: The distribution of technical efficiency in the German planning regions

Planning region		Deterministic KPF			Stochastic KPF		
Number	Name	Estimated production elasticity [a]	Technical efficiency [%]	Rank	Estimated technical efficiency [b]	Technical efficiency [%]	Rank
1	Schleswig-Holstein North	0.5685	73.07	75	0.3156	34.26	69
2	Schleswig-Holstein South-West	0.5412	69.57	80	0.2509	27.24	73
3	Schleswig-Holstein Central	0.6104	78.46	67	0.3084	33.48	70
4	Schleswig-Holstein East	0.5991	77.02	70	0.3225	35.01	67
5 & 6	Schleswig-Holstein South & Hamburg	0.6657	85.57	55	0.2301	24.98	75
7	Western Mecklenburg	0.4634	59.57	88	0.1069	11.61	90
8	Central Mecklenburg/Rostock	0.5163	66.37	84	0.1586	17.22	83
9	Western Pomerania	0.4479	57.58	91	0.0969	10.52	92
10	Mecklenburgische Seenplatte	0.4119	52.94	93	0.0900	9.77	93
11 & 13 & 15	Bremen & Bremerhaven & Bremen-Umland	0.6123	78.71	66	0.1427	15.50	84
12	East Frisia	0.5866	75.41	71	0.3166	34.37	68
14	Hamburg-Umland-South	0.6778	87.12	46	0.5835	63.34	42
16	Oldenburg	0.6008	77.22	69	0.3343	36.29	64
17	Emsland	0.5823	74.85	72	0.2955	32.08	71
18	Osnabrueck	0.6767	86.99	48	0.5572	60.49	47
19	Hanover	0.6691	86.01	53	0.4384	47.59	56
20	Suedheide	0.6290	80.85	65	0.4284	46.50	58
21	Lueneburg	0.5726	73.60	73	0.3239	35.16	66
22	Brunswick	0.7250	93.19	18	0.7056	76.60	25
23	Hildesheim	0.6713	86.29	50	0.5375	58.36	48
24	Goettingen	0.6817	87.62	45	0.5887	63.91	41
25	Prignitz-Obehavel	0.4859	62.46	87	0.1385	15.04	85
26	Uckermark-Barnim	0.4542	58.38	90	0.1201	13.04	89
27	Oderland-Spree	0.4899	62.98	86	0.1367	14.84	86
28	Lusatia-Spreewald	0.5389	69.28	81	0.1594	17.30	82
29 & 30	Havelland-Flaeming & Berlin	0.6833	87.83	44	0.4006	43.49	60
31	Altmark	0.4247	54.59	92	0.1305	14.16	88
32	Magdeburg	0.5550	71.34	78	0.1803	19.57	79
33	Dessau	0.4634	59.56	89	0.1010	10.97	91
34	Halle/Saale	0.5604	72.04	77	0.1846	20.04	78
35	Muenster	0.7112	91.42	31	0.6672	72.43	34
36	Bielefeld	0.7150	91.91	28	0.6825	74.09	32
37	Paderborn	0.6673	85.78	54	0.5199	56.44	50
38	Arnsberg	0.6692	86.03	52	0.5194	56.39	51
39	Dortmund	0.6403	82.31	58	0.3664	39.77	63
40	Emscher-Lippe	0.6768	87.01	47	0.5316	57.72	49
41	Duisburg/Essen	0.6714	86.31	49	0.4340	47.12	57
42	Duesseldorf	0.7335	94.29	12	0.7412	80.47	21
43	Bochum/Hagen	0.7171	92.18	26	0.6923	75.15	29
44	Cologne	0.7018	90.21	38	0.5612	60.93	46
45	Aachen	0.7237	93.02	19	0.7331	79.59	22
46	Bonn	0.7149	91.90	29	0.7118	77.28	24
47	Siegen	0.7049	90.61	35	0.6892	74.82	30
48	Northern Hesse	0.6353	81.66	62	0.3761	40.83	61
49	Central Hesse	0.7282	93.61	15	0.7740	84.02	15
50	Eastern Hesse	0.6306	81.07	64	0.4442	48.22	55

51	Rhine-Main	0.7107	91.36	32	0.5904	64.10	40
52	Starkenburg	0.7185	92.35	25	0.6867	74.54	31
53	Northern Thuringia	0.5008	64.37	85	0.1633	17.72	81
54	Central Thuringia	0.5658	72.74	76	0.1967	21.36	77
55	Southern Thuringia	0.5698	73.24	74	0.2437	26.46	74
56	Eastern Thuringia	0.6349	81.61	63	0.3663	39.77	62
57	Western Saxony	0.5347	68.74	83	0.1329	14.43	87
58	Upper Elbe Valley / Eastern Ore Mountains	0.6387	82.10	59	0.3310	35.93	65
59	Upper Lusatia-Lower Silesia	0.5356	68.85	82	0.1734	18.82	80
60	Chemnitz-Ore Mountains	0.6087	78.25	68	0.2751	29.86	72
61	South West Saxony	0.5520	70.96	79	0.1984	21.54	76
62	Middle Rhine-Nahe	0.7033	90.40	37	0.6495	70.51	36
63	Trier	0.6370	81.89	61	0.4652	50.50	53
64	Rhine-Hesse-Nahe	0.7220	92.81	22	0.7454	80.92	20
65	Western Palatinate	0.6619	85.08	56	0.5176	56.19	52
66	Phine Palatinate	0.7339	94.34	11	0.7852	85.25	12
67	Saar	0.6591	84.73	57	0.4473	48.56	54
68	Upper Neckar	0.7084	91.06	33	0.6271	68.07	37
69	Franconia	0.7292	93.73	14	0.7771	84.36	13
70	Middle Upper Rhine	0.6975	89.66	40	0.5730	62.21	43
71	Northern Black Forest	0.7631	98.09	3	0.8982	97.51	3
72	Stuttgart	0.7556	97.13	5	0.8445	91.68	7
73	Eastern Wuertemberg	0.7631	98.09	4	0.8954	97.21	4
74	Donau-Iller (BW)	0.6950	89.34	41	0.6046	65.64	39
75	Neckar-Alb	0.7295	93.77	13	0.7761	84.25	14
76	Black Forest-Baar-Heuberg	0.7498	96.39	7	0.8672	94.14	5
77	Southern Upper Rhine	0.7141	91.80	30	0.6990	75.88	26
78	High Rhine-Lake Constance	0.7226	92.88	20	0.7512	81.55	18
79	Lake Constance-Upper Swabia	0.7198	92.53	23	0.7159	77.72	23
80	Bavarian Lower Main	0.7254	93.24	17	0.7872	85.46	11
81	Wuerzburg	0.7083	91.05	34	0.6924	75.16	28
82	Main-Rhoen	0.7531	96.81	6	0.8655	93.96	6
83	Upper Franconia-West	0.7407	95.21	8	0.8375	90.91	8
84	Upper Franconia-East	0.6377	81.97	60	0.4228	45.90	59
85	Upper Franconia-North	0.6868	88.28	43	0.6231	67.64	38
86	Industrial Region Central Franconia	0.7167	92.13	27	0.6496	70.52	35
87	Augsburg	0.7281	93.60	16	0.8073	87.64	9
88	Western Central Franconia	0.6910	88.83	42	0.5730	62.20	44
89	Ingolstadt	0.7189	92.40	24	0.7546	81.91	17
90	Regensburg	0.7354	94.53	10	0.7973	86.55	10
91	Danube-Forest	0.6984	89.78	39	0.6731	73.07	33
92	Landshut	0.6713	86.29	51	0.5625	61.07	45
93	Munich	0.7379	94.85	9	0.7483	81.23	19
94	Donau-Iller (BY)	0.7223	92.85	21	0.7681	83.38	16
95	Allgaeu	0.7041	90.51	36	0.6924	75.17	27
96	Oberland	0.7779	100.00	1	0.9212	100.00	1
97	Southeast Upper Bavaria	0.7723	99.27	2	0.9111	98.90	2

[a] Results of negative-binomial regressions..
[b] Results of stochastic frontier estimation.

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