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Resources and Research Production in Higher Education: A Longitudinal Analysis of Chinese Universities, 2000–2010

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Abstract In this study we examined the resource–research relationship at China's research universities. The stochastic frontier production function was employed in analyses of a panel data set on a group of the most research-intensive universities in China from 2000 to 2010. Results suggested overall tight relationships between various resources (including human resources, research expenditures, and research equipment) and research publications. Distinct patterns emerged when research publications were disaggregated by fields [i.e., science and engineering (SE) vs. non-science and engineering (non-SE)] and publishing venues (i.e., domestic vs. international journals). Research publications in SE, especially those published in international journals, depended heavily on all three resources, while research in non-SE depended more on human resources. In addition, results suggested that research in SE had shifted its focus from domestic to international publications during this period.

Keywords Research production · Financial resources · Human resources · Stochastic frontier analysis

Introduction

In a global knowledge economy, colleges and universities are important players in the international marketplace of ideas and talents (Altbach and Balán 2007; Altbach et al. 2010). The importance of higher education institutions to national development has been recognized by many developing and middle-income countries worldwide. Meanwhile, colleges and universities themselves have been increasingly shaped by global competition,

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characterized by the growing popularity of international university rankings and efforts of building world-class universities (Rust and Kim 2012). These rankings and the pursuit of world-class university status, however, have met with vehement criticisms, especially from some college and university presidents, who insist that institutional quality cannot be measured by a single number (Ehrenberg 2003). University rankings are often described as inaccurate, irrelevant, and useless. Despite these criticisms, rankings are seldom ignored, perhaps for good reasons: They influence student college choice and enrollment decisions (Bowman and Bastedo 2009; Monks and Ehrenberg 1999) and transform higher education institutions and systems in a significant way (Hazelkorn 2015).

As many international university rankings (e.g., *Times Higher Education World University Rankings*, *Academic Ranking of World Universities (ARWU)* by Shanghai Jiao Tong University, and *Best Global Universities Rankings* by U.S. News and World Report) are dominated by research-related indicators, including number of publications, citations, and most cited papers, higher education institutions around the world are increasingly engaged in an arms race of research and publication, fueled by financial incentives for these research-related activities, especially in developing and middle-income countries (Varghese et al. 2014). Colleges and universities in China are good examples of this worldwide trend. The ARWU was originally designed to gauge the research performance between top Chinese universities and "world-class" universities. Being in the "top X" has become a national and institutional aspiration.

Sustained investment in higher education institutions from the Chinese government has resulted in dramatic growth in research publications over the last two decades or so (Zhang et al. 2013). According to a recent report by Thomson Reuters (Adams et al. 2013), research output from China, as measured by number of papers aggregated by the Web of Knowledge, accounted for about 11 % of worldwide research publications between 2007 and 2011.[1] In some fields such as material science and chemistry, more than 20 % of all research papers have authors from China. To put it in proper historical and comparative contexts, while in 1990 slightly over 1 % of research papers worldwide had authors from China, this proportion increased to 13 % in 2011.[2] In comparison, the United States had authors on 35 % of all papers in 1990, while this proportion fell to 26 % in 2011. More importantly, among research institutions in China, colleges and universities produced slightly over 50 % of all publications in 1990s, while this proportion approached 90 % in 2011.[3]

In this study, we examine research production at higher education institutions in China. Although studies on research production are extensive in both levels of analysis (i.e., individual, department, institution, country) and country coverage, very few empirical studies, if any, have investigated research production in Chinese universities [see Johnes and Yu (2008) and Zhang et al. (2013) for recent examples]. This study attempts to fill this void by gathering a unique dataset that provides detailed information on research production from a set of 72 Chinese universities funded and supervised by China's Ministry of Education (MOE). They are the most heavily research-oriented higher education

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[1] These numbers do not include papers published in Chinese-media journals.

[2] Authors' own calculation based on data from Thomson Reuters. The calculation does not consider number of authors and author order for a particular paper. We take total number of papers and calculate the proportion of those papers that have authors from certain countries.

[3] Authors' own calculation based on data from Thomson Reuters. Any institutions with either "college" or "university" in their names are classified as higher education institutions. This, of course, would likely under-estimate the number of research papers affiliated with colleges and universities.

institutions in China. In addition to our unique data and research context, this study contributes to the literature on research production in a number of important ways.

First, we disaggregate research publications by fields of study [science and engineering (SE) vs. non-SE] and publishing venues (domestic vs. international journals), resulting in four mutually exclusive subcategories.[4] The disaggregation is important because research production functions may vary across fields. For example, research in SE may depend more on research facilities and financial investment than research in non-SE, while the latter may depend more on human resources. The difference between domestic and international journals helps us understand how Chinese universities might have changed their strategies with regard to publishing venues, and is important in understanding the increasing presence of China in worldwide research production. Second, while previous research usually uses research expenditures in the current year (or lag forms) to predict research production, arguably what is more fundamental to research production is cumulative long-term research investment, which captures the overall research capacity of an institution. Therefore, we use research equipment as a proxy to measure overall research capacity. The combination of research expenditures and equipment provides improved insight into research production. Finally, we use panel data over a 10-year period between 2000 and 2010 and stochastic frontier models to analyze the patterns of research production in these institutions. This strategy helps us identify changing patterns of technical efficiency at Chinese universities over this important time period of fast growth in research production. Our analysis is guided by three research questions. (1) What is the relationship between resources (including human and capital resources) and research production in Chinese universities? (2) Does the pattern of research production vary by fields of study (i.e., SE vs. non-SE) and publishing venues (e.g., domestic vs. international)? and (3) Are Chinese universities becoming more or less efficient in research production over time?

Theoretical Framework and Chinese Context

As higher education institutions operate in the pursuit of excellent, prestige, and influence rather than profits (Bowen 1980), they need to acquire external resources through stable relationships with their constituencies and allocate limited internal resources to reflect their priorities (Liu and Zhang 2013). In this study, we integrate insights from organizational theory and economics of higher education to analyze the relationship between various input factors and research production at research universities in China. In particular, higher education institutions are viewed as multi-product firms that maximize excellence and prestige. Adding to these economic perspectives, we use resource dependency and neo-institutional theory to highlight the importance of research capacity building in research production.

Higher education institutions are multi-product firms (Cohn et al. 1989; Johnes and Johnes 2009). They use multiple inputs (including students, faculty, administrators, supplies, and facilities) to produce multiple outputs (including teaching and research). While simple in theory, many of those inputs and outputs are difficult to measure and quantify (Brewer et al. 2010). While student enrollment and degree production may be viewed as

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[4] Research publications are traditionally divided between SE and non-SE fields. SE fields typically include Sciences, Technology, Engineering, and Mathematics, while non-SE fields include Social Sciences, Arts and Humanities, Business, and Education. As in many other studies, the use of "non-SE" simply indicates the division of broad research fields and does not reflect bias toward any particular fields.

primary functions in many colleges and universities, research-intensive universities also engage in research production, as evidenced in differences in revenue composition among different types of higher education institutions (Leslie et al. 2012). An important yet unanswered question is how higher education institutions organize and prioritize their resources to produce these multiple outputs.

The revenue theory of costs (Bowen 1980) suggests that universities spend all the money they can raise to maximize excellence, prestige, and influence. With no clear definition and standard of these abstract goals, this view does not offer strong predictions regarding how colleges and universities would prioritize their resources to produce outputs that maximize prestige. Empirical studies along this line, however, suggest that research-intensive universities tend to use their internal resources to invest in research that builds institutional reputation (Ehrenberg et al. 2007; Zhang and Ehrenberg 2010). Goodall (2009) provides empirical evidence that appointing accomplished scholars as institutional leaders indeed improves research quality at higher education institutions.

While economic theories suggest that research-intensive institutions are involved in producing multiple outputs and prioritize resources to maximize institutional prestige, these theories do not tell us how institutional behaviors are influenced—and in the Chinese context that we will discuss below, shaped—by external forces. Resource dependence theory posits that an educational institution engages in direct exchange relations with many agents in order to acquire the resources necessary to accomplish its missions (Pfeffer and Salancik 1978). Agents who control critical resources can impose preferred values and practices by linking compliance with resource allocation. From this view, the central government in China can strongly influence higher education institutions by providing the lion's share of financial resources. Finally, neo-institutional theory posits that organizations behave in accordance with norms and standards of their field, even when such similarities would not yield a competitive advantage on individual organizations (DiMaggio and Powell 1983). For research-intensive universities, the theory predicts that they would emphasize research and publication in the pursuit of institutional prestige (Leslie et al. 2012).

To obtain an adequate understanding of the environment in which research universities in China operate, a brief historical review of policies pertaining to higher education is in order. In the early years soon after the founding of the new China in 1949, universities were consolidated, using their peers in the Soviet Union as models (Hayhoe 1996). By the end of 1955, a new research system had been established with the Chinese Academy of Science as its center, surrounded by higher education institutions. In the subsequent decade (1956–1965), a series of political events (e.g., March toward Science, the Anti-rightists Movement, and the Great Leap Forward) first facilitated but then hindered growth in the scientific research community and higher education institutions (Cui 2000). Research activities came to a complete halt during the Cultural Revolution (1966–1976). Up to this point, the primary function of higher education institutions in China was to train a strong workforce for economic development; research and publication were considered as peripheral to colleges and universities. A search of publication data provided by Thomson Reuters' Science Citation Index revealed 48 publications authored or coauthored by Chinese scholars in 1975; only about 30 % of these publications were affiliated with higher education institutions.

The year 1978 was a turning point in China's modern history, with a 10 % annual rate of economic growth since reform and open-door policy were adopted. A series of research and development policies were enacted that promoted impressive achievement in scientific research. During the 1990s, the role of higher education institutions in research and

development was emphasized, with the goal of revitalizing the nation through science, innovation, and education. Increasingly, R&D input was viewed as productive investment because the outputs of research activities—patents, scholarly papers, and project achievements—were all knowledge properties that possessed the feature of productivity. To accelerate R&D development, higher education institutions were evaluated and re-invested. Among various efforts and initiatives, the "211 Project" and "985 Project" were most notable.

The "211 Project" was launched in 1995. Its aim was to build high-level national universities by improving their capacity in teaching, research and public service. The project selected universities according to an evaluation of their status and strength in academic discipline and subjects. As more and more institutions applied to join this project, the project eventually included 116 universities. Selection into the "211 Project" was accompanied by special grants from both central and local governments. From 1995 to 2000, the "211 Project" took in almost 10.9 billion CNY (about $1.3 billion). As resources flowed into these institutions, they were able to consolidate their advantageous positions in China's higher education system. The value of equipment, number of books and research funds in those higher education institutions, were 54, 31 and 72 % of national totals, respectively. Moreover, the "211" institutions gained large advantages in fostering new talents. The numbers of doctoral and master students were 84 and 69 % of national totals (Dong et al. 2007).

On the basis of the "211 Project," the "985 Project" was established in 1998. Compared with the "211 Project," the "985 Project" was even stricter in its selection criterion. The "985 project," with a total of 39 member institutions, included only those universities that are ranked among the top in the nation, overall or in specific disciplines (e.g., Agriculture, Forestry, Geosciences, etc.). The project focused on building "world-class" research universities through developing several of the world's leading academic disciplines and subjects. To achieve this grand goal, "985" institutions acquired much more support and many more resources from the Chinese government than those included in the "211 Project." "985" institutions in Phase I (1998–2003) acquired as much as 25.5 billion CNY (about $3 billion) from the central government; grants for Phase II (2004–2009) were as high as 42.6 billion CNY (about $5.3 billion) (Yang 2009). The "985 Project" is considered one of the largest sustained investments in higher education in human history (Zhang et al. 2013). These government-organized efforts have greatly spurred research and publications. For example, publication data provided by Thomson Reuters' Science Citation Index indicate that from 1990 to 2011, the number of publications authored or coauthored by Chinese researchers increased from about 6000 to 152,000. More importantly, the proportion of publications affiliated with higher education institutions increased from about 50 % in 1990 to 90 % in 2011. In other words, higher education institutions have firmly established their central roles in producing scientific research.

Meanwhile, the release of the *Academic Ranking of World Universities* by Shanghai Jiao Tong University in 2003 facilitated an environment in which research and publications in internationally recognized journals were used as the primary instruments in evaluating the academic strength of higher education institutions in China. For many research universities, publishing in international journals has become the new norm and standard. The force of institutional isomorphism is operating at its best in the case of research universities in China because they represent the upper echelon of higher education institutions in the nation and they all aspire to be world-class universities. Therefore, in this study we expect to see greater increases in the number of research papers in international journals than in domestic journals published by Chinese research universities in recent years.

The theoretical framework discussed in this section emphasizes the centrality of resources in research production. Empirical analyses on research production have examined the impact of various human and financial resources on research production (Leslie et al. 2012; Zhang and Ehrenberg 2010). In empirical studies, human resources typically included faculty of various types, graduate and undergraduate students, while financial resources included primarily internal and external research expenditures. In this analysis, we follow this line of research by including an array of human and financial resources. Importantly, by disaggregating research publications by fields of study, this analysis provides a more nuanced view on the importance of resources across different fields of studies.

Literature Review

Research production and performance in higher education institutions have been examined at individual, departmental, and institutional levels. Individual-level analyses have examined variations in faculty research productivities. For example, Bellas and Toutoushian (1999) find in a nationally representative sample of postsecondary faculty that research productivity varies considerably by gender, race/ethnicity, and family status. Other studies have used data from a single institution or department to understand how faculty research productivity might also be influenced by organizational factors. Results along this line suggest that faculty research productivity is also influenced by various department and institutional characteristics, including team organization (Rey-Rocha et al. 2002), department climate, age structure, and proportion of faculty members with PhDs in a department (Smeby and Try 2005), and effective leadership (Bland et al. 2005).

Department-level analyses have been conducted to look for variations in the research productivity of similar departments or programs across higher education institutions. For example, Jordan et al. (1988), using data from economics departments, find that research productivity, measured by average number of published research papers per faculty, varies by institutional control and department size. In particular, average productivity is higher at private institutions and in larger departments. These results are echoed by Dundar and Lewis (1995, 1998), who find that department productivity is positively associated with faculty-group size, being in a private institution, having a larger number of full professors, and having a larger percentage of faculty actively publishing in peer-reviewed journals.

Most studies on research production and performance have been conducted at the institutional level (e.g., Adams and Clemmons 2006; Charlton and Andras 2007; Zhang and Ehrenberg 2010). These studies have typically shown that institution-level research production is a function of various financial and human resources. Financial resources (e.g., research expenditures) are directly related to research activities and thus an obvious factor affecting research production. Agasisti and Johnes (2010) use current expenditures during the year as a research input. Lagged research expenditures are also used to predict future research production (Adams and Clemmons 2006; Zhang and Ehrenberg 2010). Instructional expenditures may also contribute to research production. Graves et al. (1982) suggest that faculty salary, which is counted as an instructional expenditure, is an incentive that leads to greater production of research publications. Instructional expenditures can also figure into the research process via the relationship between student enrollment and research production (Adams and Clemmons 2006).

Human resources include those directly engaged in research activities (e.g., research faculty, graduate students) and those indirectly affecting research production (teaching faculty, undergraduate students). Usually, it is difficult to distinguish research and non-research faculty due to data limitations. Consequently, researchers have adopted approaches to identify which types of faculty members actually contribute to research production. Zhang and Ehrenberg (2010) find that full-time faculty members who are tenured or on tenure-track are the primary group generating external R&D funding while those not on tenure-track are negatively associated with external R&D funding. This indicates the necessity of dividing faculty into different categories since they exert different influences on research production. Similarly, undergraduate students and graduate students may have different relationships with research production. Undergraduates are linked to teaching load, which in turn may lower faculty research production. Graduate students may contribute to research in much more complicated ways—teaching assistants may help lower a teaching load but research assistants may inhibit research by being very time-consuming (Graves et al. 1982). Since graduate students in Chinese universities are required to publish a certain number of papers before graduation and most are engaged in research from their first year, we expect the relationship between graduate students and research production to be positively related.

One issue that is particularly germane to this study is the measurement of research production. Previous studies have used both input (e.g., research grants & contracts, research expenditures) and output measures (e.g., publications, patents). Research grants and contracts and research expenditures, which are inputs into the research process, are considered to be useful indicators of research production by some researchers. Johnes (2008) contends that the approach of using revenues received for research purposes as the measure of research output has the advantage of data availability and of reliability as up-to-date measures of research quality and quantity. Similarly, Agasisti and Johnes (2010) advocate use of research grants as a good measure of the market value of research because they provided a conflation of the quality and quantity of research effort, given the absence of research assessment data in Italy. Although research inputs have been accepted as a tenable measure of research production, they have various limitations. Recent research further suggests that although revenues from different sources are mainly used for their intended purposes, there are significant cross-subsidies between different functional areas of higher education institutions (Leslie et al. 2012).

Output measures (e.g., publications and patents) assess research production in a direct way. Publications can be measured by number of publications, pages, citations, etc. The number of publications is usually used in the literature to indicate the overall "pool" of current expertise at an institution (Graves et al. 1982; Toutkoushian et al. 2003) and for operationalizing and quantifying research output in the absence of available data sources on other types of research output in a transnational study (Kalaitzidakis et al. 2004). Studies have also taken co-authorship and author affiliation into consideration by allocating articles according to number of authors and institutional affiliation (Adams and Clemmons 2006; Kalaitzidakis et al. 2004). Number of citations is another measure of research output. Adams and Clemmons (2006) use cumulative citations over the first 5 years after initial publication to standardize citations received and provide a quality dimension for research output. Finally, patents are sometimes used as a measure of research production (Chellaraj et al. 2005). Generally speaking, output measures, when available, are thought to be superior than input measures.

Data and Methods

Data and Variables

Higher education in China has dramatically expanded from 2000 to 2010, with the number of higher education institutions increasing from 1041 in 2000 to 2358 in 2010. Total enrollment increased from about 5.56 million in 2000 to 22.32 million in 2010. The system is predominantly public, with private institutions serving a minor, supplemental role. Among all higher education institutions, a subset of most comprehensive and prestigious institutions, a total of 72 institutions, are funded and supervised by the MOE. We collected data on various aspects of these 72 institutions in every year between 2000 and 2010. Data elements included student enrollment, faculty employment, revenues and expenditures, and research outputs. For reasons such as institution merging and missing data, we succeeded in collecting data from the vast majority of these institutions (e.g., the exact number of institutions vary between 67 and 71), resulting in a final analytical sample of 748 observations across 11 years.

Table 1 lists the main dependent and independent variables used in this analysis, together with their descriptive statistics in 2000 and 2010. Our main variable of interest is research production, measured by number of research articles published in journals. For each institution in our sample, we collected data on number of research publications, further disaggregated by SE versus non-SE and by domestic and international journals, resulting in four mutually exclusive subcategories.

Research production involves various human and financial resources. Previous studies have demonstrate that faculty are one of the main determinants of research production. Our

Table 1 Descriptive statistics for main variables, 2000–2010

Variable	2000		2010	
	Mean	SD	Mean	SD
Total publications	1877	1645	4185	3161
Publications in SE, domestic	1096	1109	1957	1902
Publications in SE, international	236	339	1175	1232
Publications in non-SE, domestic	531	536	1007	881
Publications in non-SE, international	15	34	46	72
Research faculty	1226	835	1840	850
Research faculty in SE	934	632	1408	730
Research faculty in non-SE	434	316	564	294
Lecturers and instructors	246	200	122	80
Graduate students	2601	2254	9698	5209
Undergraduate students	13,040	7917	18,785	9244
Research equipment	17,144	12,780	48,577	28,777
Research expenditures (in 1 M CNY)	78	96	658	628
Instructional expenditures (in 1 M CNY)	347	274	950	561

Research expenditures and instructional expenditures are in 2010 constant CNY. 1 US dollar is approximately 8.3 CNY in 2000, and 6.8 CNY in 2010

data included number of research faculty (who teach and conduct research) and lecturers and instructors (who teach only) for each institution. Ideally, we would like to have the number of research faculty disaggregated by SE versus non-SE because we wished to conduct separate analyses for these two fields. Since these disaggregated data were not available, we adopted the following alternative. For each institution, we collected data on total R&D workforce (including research faculty, lab assistants, and office personnel) disaggregated by SE versus non-SE. About 80 % of institutions provided these detailed data. Then we used share of R&D workforce in SE over total R&D workforce to estimate the number of research faculty in SE, assuming that share of R&D workforce in SE is similar to share of research faculty in SE. It is possible that the actual share of research faculty in SE might be higher or lower than these estimated shares. Therefore, in the actual analysis, we tested the sensitivity of this assumption by adding or subtracting 5 and 10 % to the estimated share. The results are very similar to what are reported here. We hypothesized that research production in SE (or non-SE) depends heavily on research faculty in SE (or non-SE). The impact of lecturers and instructors is less straightforward. On the one hand, increased usage of teaching faculty may reduce the teaching load for research faculty and leave the latter with more time for research. On the other hand, increased usage of teaching faculty may also indicate an increased demand for teaching, a likely scenario in light of the dramatic expansion of college enrollment in China over the last 2 decades or so. An increased demand for teaching may cause research activity to decline. Student enrollment could also affect research production. The more time faculty spend teaching classes, the less time they have to spend on research; however, graduate students can work as teaching and research assistants and support faculty research. Therefore, we hypothesized that research production at an institution is positively related to its graduate enrollment but negatively related to its undergraduate enrollment.

Research production, especially in SE fields, heavily depends on research investment. We collected data on research equipment at each institution in addition to research expenditures in the current year. The combination of these two measures of research investment provided valuable insights into research production. Finally, we included instructional expenditures in the model because the salaries of research faculty (who teach and conduct research at the same time) are typically counted as instructional expenditures.

Methods

In economic production theory, a firm's input and output combinations are presented using a production function, which describes the maximum amount of output (i.e., the production frontier) that can be obtained from a set of given inputs. Therefore, production functions differ from ordinary least squares (OLS) regression models that estimate average output levels given a set of inputs. In estimating production frontiers, two techniques have been widely used, namely, data envelopment analysis (DEA) and stochastic frontier analysis (SFA). While both techniques estimate production frontiers, they are different in their approaches. For example, DEA is non-parametric and does not assume particular functional forms and distributions of error terms; as a result, statistical inferences can be difficult to achieve. By contrast, the parametric approach of SFA assumes particular distributions of errors and the functional forms of production technology, which allow statistical inferences (Johnes 2004). In this study, we chose to use SFA to estimate the research production frontier because we were especially interested in estimating the

relationship between various inputs including human and financial resources on research production. Since the publication of seminal work by Aigner et al. (1977), the literature on SFA has rapidly grown. Kumbhakar and Lovell (2000) and Belotti et al. (2012) provided outstanding surveys of recent theoretical developments and empirical studies using this method. The application of SFA has also been growing in higher education. Researchers have used this technique to estimate cost (Johnes and Johnes 2009; Robst 2000, 2001; Stevens 2005) and enrollment (Titus and Pusser 2011).

The application of production function to research production at colleges and universities, however, entails two potential risks. First, colleges and universities are multiple-output institutions, typically engaged in teaching, research, and services. As a result, a production function that examines only one aspect of university production could be inherently incomplete and problematic. It is not clear to what extent the research production can be separated from the production of other outputs, although recent literature in this area typically treats research production as a fairly independent function of universities (Abbott and Doucouliagos 2003; Johnes and Johnes 1993; Worthington and Lee 2008; Lee 2011). In this analysis, we followed the literature and assumed that research is a separable production at these universities. This approach, however, does not suggest that other functions especially teaching are not important. In fact, between 2000 and 2010, the average undergraduate enrollment at these research universities in China has increased by over 40 % while the average graduate enrollment almost quadrupled. Treating research as a separable function nonetheless is an important drawback of this analysis.

Formally, institutions organize resources (i.e., human and capital resources) to produce research (i.e., publications); a stochastic frontier model can be written as:

$$y_{it} = \alpha_0 + x_{it}\beta + v_{it} - u_{it} \tag{1}$$

where y_{it} represents research output (i.e., publications) for ith institution in year t; and x_{it} represents various resource inputs for the same institution in year t, including number of research faculty, lecturers and instructors, graduate and undergraduate students, research equipment, research and instructional expenditures. In empirical analysis, these input and output variables are transformed by taking the natural logarithm of each of these measures. The production of research, however, is not deterministic; it also depends on two error terms. The first term v_{it}, which is similar to random error in regression analysis, represents random shocks that occur to the production process at institution i in year t; this error term can be either positive or negative. The second term u_{it}, which represents institution i's technical inefficiency in year t, must be positive; that is, each institution cannot produce more than the maximum output obtainable. The first error term is assumed to be normally distributed and the second is the absolute value of a normally distributed error (or other distributional forms such as exponential).

Equation (1) does not consider any panel data treatment—i.e., save for subscripts, Eq. (1) is identical to the frontier function for a cross-sectional sample. Schmidt and Sickles (1984) and Kim and Schmidt (2000) assumed that institutions have time-invariant technical inefficiency over time, i.e., $u_{it} = u_i$. Consequently, the above equation can be rewritten as:

$$y_{it} = \alpha_0 + x_{it}\beta + v_{it} - u_i \tag{2}$$

As such, any unobserved institutional heterogeneity is contained in the time-invariant factor. The time-invariant nature of the production inefficiency term is problematic because institutions may be more or less efficient over time, which is especially true in the

presence of relatively long panels. Researchers have proposed various time-variant models, including quadratic specifications (Cornwell et al. 1990), a set of time dummies (Lee and Schmidt 1993), and other functional forms involving time (e.g., Battese and Coelli 1992; Kumbhakar 1990) to address this potential problem. Perhaps the most used model is the "time decay model" proposed by Battese and Coelli (1992):

$$u_{it} = \{\exp[-\eta(t - T_i)]\}u_i \qquad (3)$$

where η is an unknown parameter to be estimated, and T_i represents the number of time periods in which the ith institution is involved in production. Since one objective of the SFA is the estimation of inefficiency, using time-decay model would allow us to analyze how inefficiency changes over time. In this analysis, we mainly used the above three models (i.e., Eq. 1 pooled model, Eq. 2 time-invariant model, and Eq. 3 time decay model) to estimate the resource–research relationship. We also estimated an array of time varying models to check the robustness of our estimates.[5]

Results

Descriptive Analyses

Table 2 reports the average number of publications in our final sample of universities between 2000 and 2010. The total number of publications is also disaggregated by SE versus non-SE and domestic and international journals. These time trends are graphically presented in Fig. 1. The average number of publications in these institutions increased from 1877 in 2000 to 4185 in 2010, posting an increase of 123 % or an annual rate of 8.35 % during this 10-year period. Looking into where these papers were published reveals some interesting patterns. SE publications in domestic journals represented the largest category in all years, but the gap between SE publications in domestic and international journals shrunk considerably. During this 10-year period, the number of domestic SE publication increased by 78.60 % or an annual rate of 5.97 %, while that of international SE publications increased by almost four times or an annual rate of 17.40 %—approximately three times the annual rate of increase in domestic SE publications. On the non-SE side, although the annual rate of increase in international journals was more impressive than that for domestic journals (12.04 vs. 6.61 %), the average number of international non-SE publications remained very low in 2010. In fact, in any given year, the number of international non-SE publications only accounted for approximately 1 % of total publications. These time trends suggest that total number of publications disguises significant variation by fields of study and publishing venues, necessitating detailed, separate analysis for each subcategory of publications.

One way to examine the increase in research publications is to compare it with increases in research inputs such as human and financial resources. To illustrate, we included average research expenditures at those institutions from 2000 to 2010. (We do not argue that research expenditure is the only factor that matters, as we included a variety of inputs in our empirical models. This simple comparison does provide useful information on how the increase in research publications stacks up against increases in other input factors.) The last column in Table 2 indicates that average research expenditures at our sample institutions increased from

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[5] These additional time varying models include those proposed by Pitt and Lee (1981), Battese and Coelli (1988, 1992), Kumbhakar (1990), and Greene (2005). See Greene (2005) for a detailed discussion on similarities and differences among these models.

Table 2 Average number of research papers and research expenditures, 2000–2010

Year	Total	Domestic SE	International SE	Domestic non-SE	International non-SE	Research expenditure
2000	1877	1096	236	531	15	78
2001	2059	1127	268	653	10	91
2002	2280	1264	299	703	15	112
2003	2578	1436	371	752	19	136
2004	2823	1487	494	822	21	156
2005	3021	1625	545	829	22	180
2006	3553	1912	700	912	28	204
2007	3822	2023	831	938	31	233
2008	4107	2032	1039	999	37	494
2009	4233	2038	1143	1009	42	606
2010	4185	1957	1175	1007	46	658
Overall change (%)	122.92	78.60	397.53	89.72	211.73	743.45
Annual rate (%)	8.35	5.97	17.40	6.61	12.04	23.77

There is a jump in research expenditures in 2008, due mainly to two reasons. First, the Chinese government published the "National medium and long-term Science and Technology Development Plan (2006–2020)" in 2006 and revised the Law of China on Science and Technology Progress in 2007 to increase the investment in science and technology research activities and the proportion of expenditure on science and technology in GDP. Second, a reform of government revenue and expenditure classification was carried out in 2007 and was applied to the field of science and technology, i.e., more accounting items related to research activities were added to research expenditures

approximately 78 million CNY in 2000 (2010 constant money; 1 US dollar is approximately 8.3 CNY in 2000) to 658 million CNY in 2010 (1 US dollar is approximately 6.8 CNY in 2010). During this 10-year period, research expenditures increased at an annual rate of 23.77 % after adjusting for inflation, suggesting that the increase in research publications is actually behind the increase in research investment. Further analysis using stochastic frontier analysis is needed to examine whether institutions become more or less efficient in producing research publications given changes in various research inputs.

Total Research Publications

Table 3 examines production of total publications. Three variations of the stochastic frontier models were estimated using the same set of independent variables. All variables were transformed by the natural logarithm, so the estimated coefficients can be interpreted as elasticities, i.e., the percent change in the outcome variable given one percent change in the independent variable. The pooled model, which did not account for the panel nature of our data, generated different results than the time-invariant and time decay models, both of which account for unobserved institutional heterogeneity. The time-invariant and time decay panel data models generated slightly different results, which is not surprising given that the estimate of η in the time decay model is negative and statistically significant at −0.068, suggesting that during this 10-year period, institutions in our sample became less efficient in producing research publications. This finding is consistent with our observations in Table 2, where increases in publications were compared with the increase in one of the research input factors.
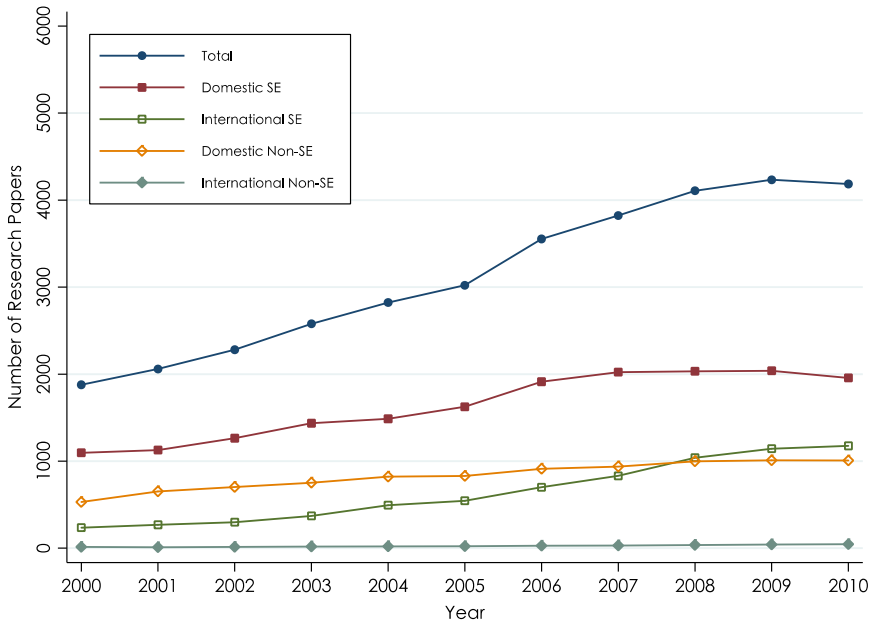
Fig. 1 Average number of publications per institution, 2000–2010

Table 3 Research production at Chinese universities (total number of research papers), 2000–2010

	Pooled	Time-invariant	Time decay
Constant	−1.479 (0.328)***	−1.022 (0.542)[+]	−1.143 (0.460)*
Research faculty	0.548 (0.068)***	0.665 (0.092)***	0.575 (0.080)***
Lecturers and instructors	−0.052 (0.018)**	−0.058 (0.021)**	−0.068 (0.021)**
Graduate students	0.271 (0.035)***	0.124 (0.046)**	0.265 (0.048)***
Undergraduate students	0.109 (0.049)*	0.051 (0.058)	0.062 (0.057)
Research equipment	0.179 (0.047)***	0.211 (0.057)***	0.166 (0.055)**
Research expenditures	0.070 (0.021)***	0.022 (0.024)	0.069 (0.024)**
Instructional expenditures	−0.008 (0.040)	0.066 (0.050)	0.020 (0.047)
η			−0.068 (0.014)***
Log-likelihood	−273	−228	−213
N	748	748	748

Standard errors in parentheses

[+] $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

   Since both the t test on the time effect η and the likelihood ratio test between the time-invariant and time decay models (LR = 28 with 1 degree of freedom) favors the latter, the time decay model is our preferred specification. Results from the time decay model suggest that publication production depends heavily on a variety of human and financial resources. The time decay model proposes that a 10 % increase in the number of research faculty is associated with a 5.75 % increase in total publications. This is consistent with previous

studies that found full-time professorial faculty to be the main drivers of research production (Zhang and Ehrenberg 2010). Numbers of lecturers and instructors do not contribute to publication production; in fact, our models suggest that number of lecturers and instructors had a negative albeit small effect, i.e., a 10 % increase in the number of lecturers and instructors is associated with a 0.68 % decrease in total research publications. One possible explanation is that the presence of a larger number of lecturers and instructors is evidence of greater instructional demand at an institution, which reduces the research production of research faculty (Lee 2011).

Graduate students also contribute significantly to research production. A 10 % increase in graduate enrollment was associated with a 2.65 % increase in research publications. We caution that this positive relationship may be endogenous in that institutions with greater volumes of research activities are likely to enroll more graduate students (Ehrenberg et al. 1993). Undergraduate students, however, did not seem to be associated with research production. Various lag terms in student enrollment variables were used to examine the temporal dimension of this relationship; however, the estimated coefficients were very similar to those reported here.

Research and financial resources also matter. Research equipment, an indicator of overall research infrastructure and capacity, had a large and positive effect on research publications. On average, a 10 % increase in the research equipment inventory was associated with 1.66 % increase in research production. Research expenditures in the current year, however, had a smaller (10 % increase in research expenditures was associated with 0.69 % increase in research production), albeit positive and significant effect on research production. This makes sense because research production probably depends more on existing overall research infrastructure rather than temporary research investment. In that sense, current research expenditures may improve future research production by investing in and improving the overall research infrastructure (Adams and Griliches 1998). To test these hypotheses, we re-ran our model using lag terms for both research equipment and expenditures. Without exception, results suggested that both were strong predictors of research production, with estimated coefficients for research equipment considerably larger than those for research expenditures. Finally, instructional expenditures did not matter.

We used different samples of institutions and model specifications to check the robustness of our findings. Recall that the number of institutions in our final sample varied slightly between 67 and 71 over the years; a consistent sample consisted of 66 institutions. Regression analyses based on these institutions yielded very similar results as reported in Table 3. In addition, one disadvantage of using SFA is the assumption of error distributions and model specifications. Therefore, we used a variety of model specifications of stochastic production analysis, including those proposed by Pitt and Lee (1981), Battese and Coelli (1988, 1992), Kumbhakar (1990), and Greene (2005). Results from this set of models are presented in Appendix Table 6. These models, except for the pooled model, generated more or less similar results.

Research Production by Fields and Publishing Venues

In the next step of the analysis, we estimated our preferred time decay model for each of the four categories of publications. We used the number of research faculty in SE and non-SE separately in these models. Because data on the number of faculty by fields were not available for some institutions, the sample size dropped to 652 in this set of analysis. Results in Table 4 reveal distinct production patterns for different categories of publications. Not surprisingly, the production of research publications in SE depends more heavily on number of research faculty in SE than in non-SE. For example, a 10 % increase in the

number of research faculty in SE fields was associated with a 3.78 % increase in domestic SE publications and a smaller increase (1.92 %) in international publications. Not surprisingly, the effect of research faculty in non-SE fields is much smaller. In fact, their effect on domestic SE publications is estimated to be negative. For international publications, a 10 % increase in the number of research faculty in non-SE fields was associated with a 1.29 % increase in research publications. As in the aggregate model, lecturers and instructors did not seem to matter.

Graduate students had positive effects on both domestic and international publications, although the effect is large on international publications. We were not able to separate graduate students in SE and non-SE fields. Had we done so, we would expect graduate students in SE fields to contribute more to SE publications than those in non-SE. Undergraduate students did not contribute to research publications. In fact, in the case of international SE publications, undergraduate students had a negative effect. Again, not surprisingly, SE publications depended heavily on the presence of research equipment. The relationship between research equipment and international SE publications was especially tight. A 10 % increase in research equipment was expected to increase research publications in international SE journals by 7.33 %. In comparison, research expenditures in the current year had a relatively small effect on SE publications. Finally instructional expenditures did not contribute to SE publications.

For non-SE publications, production depended heavily on research faculty in non-SE fields. For example, a 10 % increase in the number of research faculty in non-SE fields was associated with a 3.67 % increase in domestic publications and a 4.45 % increase in international publications. Graduate students also contributed positively to research production in non-SE publications. Lecturers, instructors, and undergraduate students did not matter. Most interestingly, while research equipment had a significant impact on SE

Table 4 Research production at Chinese universities, by fields and publishers

	Domestic SE	International SE	Domestic non-SE	International non-SE
Constant	−1.712 (0.699)*	−3.995 (1.039)***	2.659 (0.925)**	−3.772 (1.780)*
Research faculty in SE	0.378 (0.059)***	0.192 (0.085)*	−0.009 (0.051)	−0.107 (0.102)
Research faculty in non-SE	−0.048 (0.041)	0.129 (0.066)$^{+}$	0.367 (0.051)***	0.445 (0.107)***
Lecturers and instructors	0.029 (0.034)	−0.053 (0.048)	0.017 (0.031)	−0.117 (0.075)
Graduate students	0.158 (0.076)*	0.405 (0.120)***	0.257 (0.076)***	0.349 (0.160)*
Undergraduate students	0.084 (0.091)	−0.333 (0.124)**	0.062 (0.085)	−0.341 (0.184)$^{+}$
Research equipment	0.411 (0.111)***	0.733 (0.148)***	−0.178 (0.095)$^{+}$	−0.123 (0.195)
Research expenditures	0.236 (0.044)***	0.132 (0.059)*	0.058 (0.038)	0.186 (0.086)*
Instructional expenditures	−0.165 (0.068)*	−0.006 (0.100)	0.098 (0.066)	0.545 (0.153)***
η	−0.140 (0.022)***	0.028 (0.012)*	0.009 (0.005)	−0.004 (0.012)
Log-likelihood	−458	−647	−374	−882
N	652	652	652	652

Standard errors in parentheses

$^{+}$ $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

Table 5 Estimated technical efficiency by types of institutions over years (%)

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Total											
985	84.25	83.29	82.28	81.22	80.10	78.94	77.72	76.44	75.12	73.74	71.77
211	75.68	74.31	73.27	71.81	70.28	69.11	67.08	65.39	63.66	61.88	60.05
Difference	8.57	8.98	9.00	9.41	9.82	9.83	10.64	11.05	11.46	11.86	11.71
Domestic SE											
985	81.21	78.89	76.35	73.60	69.36	66.13	62.72	59.16	55.47	51.70	46.66
211	83.11	80.64	78.22	76.30	73.50	70.56	65.42	63.20	58.36	54.53	50.84
Difference	-1.90	-1.75	-1.87	-2.70	-4.14	-4.43	-2.70	-4.04	-2.89	-2.82	-4.18
International SE											
985	56.47	57.26	58.04	58.82	58.07	58.83	59.59	60.34	61.08	61.82	62.04
211	39.46	39.23	40.09	39.95	40.81	42.88	41.08	41.54	42.76	44.01	44.44
Difference	17.02	18.03	17.95	18.86	17.25	15.95	18.51	18.80	18.33	17.81	17.61
Domestic non-SE											
985	41.40	41.66	41.92	42.18	43.71	43.97	44.22	44.48	44.73	44.99	44.87
211	21.78	23.00	23.26	23.32	23.58	23.37	24.70	26.32	25.23	25.91	25.77
Difference	19.62	18.66	18.66	18.86	20.13	20.60	19.53	18.16	19.50	19.07	19.10
International non-SE											
985	37.79	37.67	37.55	37.43	38.54	38.42	38.31	38.19	38.07	37.96	37.23
211	21.39	21.68	21.57	20.91	20.80	20.06	22.20	22.01	21.97	21.20	21.74
Difference	16.40	15.99	15.99	16.52	17.75	18.36	16.11	16.18	16.11	16.76	15.49

research production, it had no effects on research publications in non-SE fields. Research expenditures had a positive and significant effect on international non-SE publications, but not on domestic non-SE publications. Finally, while instructional expenditures did not seem to affect SE publications, they had a positive effect on non-SE publications.

The time decay models also yielded insights into research production trends during the 10-year period. The estimates for time-varying factor η indicated that our sample institutions had become less efficient in producing domestic SE publications, but more efficient in producing international SE publications. The opposite direction of change in domestic and international SE publications was intriguing. Further explanations are offered in the next section. In both domestic and international non-SE publications, the time effects were not significant.

Technical Efficiency of "985" and "211" Institutions

In calculating the technical efficiencies of our institutions, we were particularly interested in comparing efficiency between "211" and "985" institutions. Although both "211" and "985" institutions receive preferential treatment in public funding allocations, "985" institutions receive further priority. All 39 "985" institutions were included in our sample. Based on these differences, not only would "985" institutions be more productive in research, but they would also have different strategies (e.g., domestic and international journals) for publishing their research due to their focus on international competitiveness.

Results in Table 5 reveal some interesting patterns between "985" and other "211" institutions over time. In terms of total publications, these institutions were producing research at a relatively high efficiency level—on average, about 80 % of their maximum production level in 2000 and 70 % in 2008. This suggests that technical efficiency had been decreasing over time for these institutions. The decline, however, was not uniform across our subcategories of publications. The main decline happened in domestic SE publications, especially after considering that this category represents the largest share of total publications. By contrast, these institutions became more efficient in producing international SE publications. On the non-SE side, production efficiency for domestic non-SE was essentially flat over the years examined, while that of international non-SE witnessed a moderate decline. Considering that international non-SE publications constituted less than 1 % of total publication, its decline had a minimal impact on overall decline.

There are several possible reasons for the decline in technical efficiency in domestic SE. First, research, especially science research, has become increasingly expensive (Ehrenberg et al. 2007); however, this may not be the main reason because publishing in international SE journals, which arguably is the most expensive among all subcategories, has been increasing. A second possible reason is the publication capacity constraint faced by these institutions. Recall that these institutions represent the overall majority of research-intensive institutions in China—they collectively publish the majority of research articles in domestic journal outlets. Consequently, while research inputs may increase considerably over years, total number of research publications is constrained by journal capacity. This argument, however, still falls short of explaining the significant decline in production efficiency in domestic SE publications. A third explanation, which appears more reasonable to us, is a shift in focus from publishing in domestic to international SE journals over the years. This explanation is consistent with the observation that those "985" institutions, which aspire to become world-class institutions, have improved their efficiency more so than non-"985" institutions. In addition, anecdotal evidence (e.g., conversations with researchers in China) indicates that institutions provide substantial monetary and non-monetary incentives to faculty members who publish their work in international journals.

Comparing "985" and non-"985" institutions suggests that "985" institutions on average are more efficient in producing research publications. A comparison of separate categories indicates that "985" institutions have an advantage in publishing in international SE, domestic non-SE, and international non-SE journals. These observations are consistent with the more comprehensive nature of "985" institutions (as opposed to SE focused) as well as being more internationally oriented. The low production and in fact declining production efficiency in international non-SE journals is somewhat unexpected, but not entirely surprising either. Discussions with researchers in non-SE fields in China suggest that this is not due to lack of intention or incentives; instead, it is mainly due to language and other barriers.

Limitations

It is important to note a number of caveats in this study. First, universities and research universities in particular are multiple-input, multiple-output institutions. Teaching and research are the two basic functions of higher education institutions. The overall contribution of universities to the development of our society is reflected not only in the research and innovations they produce, but also in the citizens they educate. Consequently, any studies that examine only one aspect of university production could be inherently incomplete. The strength of the exclusive focus on research production in the current analysis, however, yields insight into how research production patterns vary both across categories of publications and over time. Further research may examine university production in a multi-production framework.

Second, the publication data are available only in aggregate forms in SE and non-SE fields, resulting in a number of data related limitations. For example, we were not able to control for the order of authorship or the quality of publications. Considering the rising collaborations especially international collaborations in recent decades and diverse quality of research publications, the aggregate number of publications only provides a crude measure of research production. Although the division of SE and non-SE fields provides an excellent opportunity to examine the role of human and financial resources in these two broad fields, we were not able to examine the potential variability in the relationship between resources and research production across a wide range of fields.

Third, although our empirical models have considered a variety of human and financial resources, many other factors that could affect research production were not included due to data unavailability. For example, previous studies of research production have found the importance of many individual and departmental level factors. These factors include gender, race, family, tenure status, and ranks (Bellas and Toutkoushian 1999; Bland et al. 2005; Rey-Rocha et al. 2002; Smeby and Try 2005). Although it is possible to aggregate some of these factors to the institutional level, they are not available in the data we collected. Fortunately, the panel data technique used in this analysis was able to account for institutional heterogeneity in these factors as long as they remain stable over time. While the panel data technique represents an effective strategy to control for institutional heterogeneity, ignoring these variables would still cause omitted variable bias when they vary over time (Zhang 2010).

Conclusion and Discussion

In this study we examined the resource–research relationship at China's research universities. The stochastic frontier production function was employed in analyses of a panel data set on a group of the most research-intensive universities in China from 2000 to 2010. Our

results suggest tight relationships between various resources (including human resources and research equipment and expenditures) and research publications. In particular, research publications in both SE and non-SE fields are heavily dependent upon research faculty in their respective fields. Graduate students but not undergraduate students also contribute to research production. Finally, research publications in SE, especially those published in international journals, depend heavily on research equipment—this is not the case for non-SE publications. Our results also suggest increasing emphases on international SE publications during the first decade of the 21st century.

While some of these findings are idiosyncratic to the Chinese context, many of them contribute to our understanding of the relationship between resources and research production. For example, our results reveal distinct patterns of research production between SE and non-SE fields. For example, in SE fields, research equipment and expenditures are critical elements in addition to researchers, while the production of research in non-SE seems mainly dependent upon human resources. From a research perspective, since the distribution of academic disciplines differs across institutions as missions vary, future studies comparing research productions across institution should consider differences in the composition of academic fields and differences in the role of human and financial resources in research production across fields.

From a policy perspective, the distinct patterns of research production between SE and non-SE fields and probably among different SE and non-SE sub-fields provide useful tools for policymakers who seek to prioritize resource allocations in order to improve the performance of higher education institutions. In the Chinese context, for example, increases in investment in research related to science and technology would most likely continue to generate high volumes of research outputs in the years ahead. Research production in non-SE fields, however, seems to follow a different path. The lopsided growth in SE versus non-SE fields is clearly detrimental to their worldwide university rankings. According to most recent university ranking data released by *ARWU*, quite a few Chinese universities have successfully broken into the top 50 in many science and engineering fields, while their rankings in social sciences remain low. More studies on the determinants and mechanisms of research production in non-SE fields would inform policies that facilitate efforts to build world-class universities.

These results are equally relevant for higher education institutions in the United States given the rising costs of sciences (Ehrenberg et al. 2007) and waning public support to higher education (Cohen 2007). Colleges and universities have been forced to diversify their revenue streams mainly through tuition and other private sources (Slaughter and Leslie 1997), which may have detrimental effects on basic research in the long run. Although the United States still maintains its global dominance in scientific production measured by both the quantity and quality of research publications, other countries have been catching up with a much higher growth rate (Zhang et al. 2015). Given the importance of scientific research in economic growth in an increasingly knowledge-driven economy (Goldin and Katz 2009; Nelson and Romer 1996), sustained public support is crucial for improving the human and financial resources that are required for university research.

Appendix

See Table 6.

Table 6 Stochastic production estimation of research production in Chinese universities

	Pooled	Pitt and Lee (1981)	Battese and Coelli (1988)	Kumbhakar (1990)	Battese and Coelli (1992)	Greene (2005) TRE	Greene (2005) TFE
Constant	−1.479 (0.328)***	−1.045 (0.499)*	−1.022 (0.542)+	−1.269 (0.434)**	−1.143 (0.460)*	0.045 (0.431)	
Research faculty	0.548 (0.068)***	0.668 (0.087)***	0.665 (0.092)***	0.525 (0.080)***	0.575 (0.080)***	0.546 (0.070)***	0.414 (0.072)***
Lecturers and instructors	−0.052 (0.018)**	−0.059 (0.021)**	−0.058 (0.021)**	−0.062 (0.021)**	−0.068 (0.021)**	−0.046 (0.016)**	−0.055 (0.017)**
Graduate students	0.271 (0.035)***	0.123 (0.045)**	0.124 (0.046)**	0.303 (0.046)***	0.265 (0.048)***	0.192 (0.037)***	0.203 (0.038)***
Undergraduate students	0.109 (0.049)*	0.051 (0.058)	0.051 (0.058)	0.053 (0.056)	0.062 (0.057)	0.082 (0.044)+	0.070 (0.044)
Research equipment	0.179 (0.047)***	0.210 (0.056)***	0.211 (0.057)***	0.187 (0.054)***	0.166 (0.055)**	0.165 (0.051)**	0.161 (0.053)**
Research expenditures	0.070 (0.021)***	0.021 (0.024)	0.022 (0.024)	0.049 (0.025)+	0.069 (0.024)**	0.045 (0.019)*	0.050 (0.018)**
Instructional expenditures	−0.008 (0.040)	0.068 (0.047)	0.066 (0.050)	0.036 (0.046)	0.020 (0.047)	−0.028 (0.034)	−0.038 (0.032)
Log-likelihood	−273	−228	−227	−209	−213	−105	34
N	748	748	748	748	748	748	748

Standard errors in parentheses

+ $p < 0.10$; * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$

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