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Scientific effects of large research infrastructures in China

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ABSTRACT

Large research infrastructures (RIs) are expected to play an important role in the development of scientific activities in China and the construction of China's national scientific systems. However, few studies have been devoted to the systematic evaluation of the scientific effects of China's RIs. This paper attempts to fill this gap by designing a comprehensive analytical framework composed of the input-side, output-side, process-side and environment-side effects of RIs on scientific activities. The analysis is implemented based on a novel sample composed of nine of China's typical RIs. More specifically, this paper classified these nine Chinese RIs into the following three types according to their functions: dedicated research infrastructure, public experimental platform and public infrastructure. Furthermore, this paper analyzes the features of the scientific effects of these RIs in terms of the following four typical scientific effects: science and technology advancement effect, capability cultivation effect, networking effect and clustering effect. In addition to the finding that RIs have promoted scientific advancements in many disciplines in China, the study found that RIs are important to the acquisition of new knowledge, and also contribute to the propagation of competitive scientific organizations and scientific talent. Networking and clustering impacts are also important scientific effects of RIs, as they increase the effectiveness of scientific activities in China. This paper not only contributes to developing an analytical framework for evaluating the functions and effects of large RIs but also presents evidence regarding the development of large RIs in emerging countries.

1. Introduction

Research infrastructures (RIs) have become a topic of interest and priority among funders, political bodies, and (increasingly) institutional decision makers (Lossau, 2012). Currently, with the increasing importance of RIs to science and technology development as well as to enhancing competiveness, the economic and social value of RIs has taken on even greater consequence for both developed and developing countries. Over the last half century, RIs have become an important instrument in the exploration of the frontiers of science and technology, and they have aided in the realization public value and the support of social needs. According to European Commission (2010), RIs are in the center of the knowledge triangle of research, education and innovation and serve as the most important carrier of valuable new knowledge. Thus, both developed and developing countries devote resources to building and updating RIs in scientific frontiers (ESFRI, 2006; Research Councils, 2010; Office of Science, DOE, 2003; CSC, 2013). RIs are expected to endow countries with the capability to produce world-class research to improve economic and social outcomes. In the catching-up situation, the RIs are even more important for emerging countries that want to surpass developed countries in the science and technology fields.

As a country with an emerging scientific and technological presence, China has devoted tremendous efforts to the development of RIs to support innovation-driven development. Consequently, China has played an increasingly important role in the construction and application of RIs around the world since RI construction began in China with the atomic and hydrogen bomb projects and the man-made satellite project. In China, RIs are usually described as large scientific engineering projects that are built primarily under the auspices of the Chinese Academy of Sciences (CAS), which is one of top academic research institutes in China. Due to the need for scientific and technological breakthroughs, as well as the innovation-driven development in China, RIs attract more attention and obtain more investment from the Chinese government than they have in the past. Because of the high cost of RIs and the important role they pay in economic and social development, both policy makers and officials of funding agencies are increasingly relying on formal and systematic evaluation procedures to make key decisions about implementing new projects and programs or about upgrading or even terminating existing projects. In terms of the construction of RIs, scientific effects should be a primary consideration in policy making regarding the development and management of RIs.

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Table 1
Typical definition of RI by administrative department.

Author	Definition
NSF (2013)	Large-scale networking or computational infrastructure, multi-user instruments or networks of such instruments, or other infrastructure, instrumentation and equipment having a major impact on a broad segment of a scientific or engineering discipline.
ESFRI (2011)	Facilities, resources or services of a unique nature that have been identified by European research communities to conduct top-level activities in all fields. Includes the associated human resources and covers major equipment or sets of instruments, in addition to knowledge-containing resources, such as collections, archives and data banks.
CSC (2013)	Large and complex science systems that are expected to provide exceptional research tools for exploring the unknown world, discovering scientific law and realizing technological change.

However, to our knowledge, there are very few relevant studies that evaluate the scientific effects of China's RIs in the existing literature. The processes of identifying, funding, designing, developing, constructing, managing and sharing RIs require an effective assessment of RIs. This research gap should be filled and then a more effective development path should be designed to improve the active function of China's RIs during the building of this innovation-driven nation.

Extant studies evaluating the scientific effects of RIs in developed countries depend primarily on so-called "facility metrics", which combinations of the number of publications, the operations reliability / technical performance, and the user demand for experimental time (Hallonsten, 2014). The sole bibliometric assessment of RIs has several limitations in terms of the expected function of RIs in social and economic development, and extended measures— beyond simple counts of publications, citations and costs—that aid in comprehensively assessing the scientific effects of RIs should be specifically proposed (Heidler and Hallonsten, 2015; Zuijdam et al., 2011; GSF, 2014; CAS, 2007). Consequently, an important goal of this study is to build an analytical framework for evaluating the scientific effects of RIs. The analytical framework can be used to compare and evaluate China's typical RIs and provide valuable evidence that can be useful in improving the operations and management of large RIs. The classification of Chinese RIs according to function in our analytical framework is a new and managerially useful method for comprehensively evaluating RIs. This approach can provide a comprehensive evaluation of the scientific effects of RIs in terms of input-side, output-side, process-side and environment-side impacts on scientific activities. Moreover, our focus on the diversity of RIs and the systematicness of RI effects can aid in developing different policy measures for different RIs and in classifying RIs and types of scientific effects. Our analytical framework can provide a way for policy makers to comprehensively understand the differences in the scientific effects of RIs from both functional and effect perspectives.

The rest of this paper is organized as follows. A literature review is presented in Section 2. Section 3 describes our proposed analytical framework for evaluating RI scientific effects. In Section 4, we select nine typical RIs in China, classify these RIs into three types, and comparatively analyze them using the analytical framework. A summary of four types of scientific effects and several policy suggestions are discussed in the fifth section to shed light on the governance of potential future RIs.

2. Literature review

With the increasing importance of RIs to economic and social development, the functions and outcomes of RIs are receiving greater attention from government organizations and academic researchers (e.g., Heidler and Hallonsten, 2015; Hallonsten, 2014; GSF, 2014). To better assess the effect of RIs, the chapter firstly reviews and offers a definition of RIs based on an analysis of extant definitions. Secondly, this paper reviews and compares several main perspectives on RI effects in the extant literature and discusses why scientific effects should receive more attention. Finally, we discuss the inadequacy of effect studies in the extant literature as the reason for our proposal of an analytical framework, and we then use this framework to explain the specific effects and their functions in the Chinese context.

Several organizations have proposed different definitions of RIs in the extant literature, as shown in Table 1. Clearly, different countries and organizations define RIs in different ways. This arises from the various contexts in which the term is used and the need to gain support from a full range of research endeavors. Among these definitions, those proposed by the US National Science Foundation (NSF, 2013) and the European Strategy Forum on Research Infrastructures (ESFRI, 2011) are popular in the extant literature. To facilitate the guidance and management of RIs, the Chinese State Council (CSC, 2013) has offered a definition of RIs that is related to development goals in China. Table 1 displays these three definitions. By comparing them, we find several common RI characteristics, including serving as a scientific tool, the influence of national infrastructure, and the systematic nature of RIs. Compared with normal scientific instruments, RIs feature intensive knowledge, capital, and engineering activities. For this reason, central governments are the primary funders of RIs and RIs exert more widespread influence than is typically expected of a scientific tool. Based on these considerations, this article defines RIs as large scientific instrumentation, facility, and equipment clusters that require large investments and complex engineering and networking efforts; receive funding primarily from national governments; and serve the science frontier, economic and social needs and national security. This definition is used to guide the construction of our analytical framework for evaluating the scientific effects of RIs.

There are several interesting studies about the evaluation of RI effects (see Table 2). Zuijdam et al. (2011) examined the roles and added value of RIs using the following four-type classification of effects: scientific effect, the creation of networks, economic value, and added value for society. The study investigated RIs in the Netherlands and analyzed the scientific effects in great detail. The OECD Global Science Forum (GSF, 2014) undertook a similar study of the impacts of the European Organization for Nuclear Research (CERN)—one of the most successful international RI organizations. Six impact categories were empirically defined as follows: scientific, input, training, national,

Table 2
Comparison among types of RI effects in the extant literature and descriptions of scientific effects.

Author	Types of RI Effects	Scientific Effect
Zuijdam et al. (2011)	Four aspect of added value: scientific effect, the creation of networks, economic value, added value for society.	Indispensable scientific tool, research scope and efficiency increase, multi-disciplinary research promotion, set target achievement in time, exponential increase in scientific output.
GSF (2014)	Six impact categories: purely scientific results; direct impact of RI spending; training effect; achieving national, regional and global goals; technological innovations and diffusion effect; education effect.	The most visible impact category; short-term impacts can range from spectacular to incremental; long-term impacts on science are, typically, difficult to forecast and to assess.
EC (2010)	Six impact categories: scientific, technological, economic, social, political, environmental.	Providing tools for frontier research, enhancement of research capacity, strengthening European Research Areas.
CAS (2007)	Six impact categories: scientific, national security and economic development, high-tech development, cultivating scientific talent, international cooperation, scientific competitiveness.	Providing extreme capability to solve contemporary fundamental science problems.

technological, educational and other social effects. In an analytical framework presented by the European Commission (2010), six impact categories are also developed which are scientific, technological, economic, social, political, and environmental effects. In a CAS (2007) research report, six types of effects of RIs are provided, including scientific, national security and economic development, high-tech development, cultivating scientific talent, international cooperation, and scientific competitiveness effects. It is not difficult to determine that scientific effect is the primary effect considered, and it is included in all of the four classification systems of RI effects in the extant literature. In terms of the various purposes for constructing RIs, scientific effect is the fundamental and direct function of RIs, and it influences and determines the functional level of other RI effects. Consequently, we determined that it is important and reasonable to choose the scientific effects of RIs as our focus in this paper.

The exploration of the scientific effects of RIs in extant literature has not been comprehensive, especially in the context of emerging countries. While the characteristics and effects of RIs have been studied and investigated, these studies have been at the preliminary stage. The extant literature has focused mainly on the direct, short-term scientific effects of RIs. The perspective of long-term and extended scientific effects of RIs has been neglected or simply mentioned without deep investigation. It is widely acknowledged that scientific progress and other social and economic developments are closely intertwined, and thus a comprehensive evaluation perspective is needed when considering the multi-aspect scientific effects of RIs. The complex system characteristics and public goods nature of RIs require them to function not only as a simple science tool for a research organization and certain academic users but also as a public infrastructure tool for regions, nations and society. Because the extant literature using bibliometrics and so-called facility metrics of RIs scientific effects has not provided a comprehensive framework for evaluating the scientific effects of RIs, a comprehensive analytical framework from a systemic perspective is needed. In the existing literature, several important issues have not been considered, such as the differences among RIs in terms of scientific effects. The diversity of RIs in the construction stage and in their disciplines and their functional classifications may produce different scientific effects. Moreover, relevant research in the context of emerging countries is still rare in the extant literature. In terms of our interest in this study, we were unable to find relevant research in the context of China, which is a typical emerging country and actively invests in RIs to improve its indigenous innovative capacity. Evaluation research on the scientific effects in the China's content will be valuable for guiding the development direction of RIs in this country. Additionally, this paper can provide a typical sample of emerging country for evaluating RI effects in a general sense.

3. Analytical method

Based on the diversity and complexity of RIs as well as the lack of available theories and methods for evaluating RIs, an exploratory multi-case research method is adopted in this paper. Multi-case analysis is needed when a lack of understanding about a phenomenon exists due to the inadequacy of existing theories. A multi-case analysis is carried out by using case studies as the source of data. In other words, cases are considered to be separate experiments in case studies, from which the theory can be built by iteratively looking for patterns among the cases and testing those patterns in each case via replication logic. In comparison with single case studies, multi-case research has the following advantages: the ability to observe consistent patterns that are distinct from idiosyncratic detail, more accurate levels of abstraction, the definition and measurement of constructs and better generalizability (Yin, 1994; Eisenhardt, 1989). Obviously, the multi-case method is preferred because of the differences among various types of RIs in terms of scientific effects. In constructing a multi-case sample, a representative group of RIs is needed. In terms of the criteria used to select the cases, the functional difference among RIs is the main consideration. Moreover, the RI's discipline (or disciplines) and the lifecycle stage are two supplemental factors. The lifecycle of RIs consist mainly of the following 3 stages: the pre-research stage, the construction stage (from the approval of an RI project to its acceptance by the national authority) and the operation stage (from the usage of RI to its retirement) (CAS, 2013). Because the innovation and managerial mechanisms of each stage are different, RIs in different operational stages are chosen as cases. To facilitate comparisons among different RIs, the RI cases are classified into three types according to their functional differences, where the dimension of scientific effects of RIs is extended using a systematic perspective. By using this two-dimensional combination of factors, our detailed analysis can present an in-depth differential evaluation of the scientific effects of RIs.

3.1. Classification of RIs

RIs differ in terms of their functions. As a science tool, RIs may serve a single discipline, multiple disciplines and other public needs as well. To better illustrate the scientific effects of different RIs, we propose a classification from the functional perspective, which refers to the practical management experience in the Chinese context (mainly from CAS managerial experience). Chinese RIs are divided into the following 3 categories: Dedicated RI (D-RI), Public Experimental Platform (PEP) and Public Infrastructure (PI).

a) *Dedicated RIs* (D-RIs) are developed to address the major science and technology objectives of a specific discipline. This type of RI has the convergent and single scientific objective of a single discipline. Examples of dedicated RIs include the Large Collider, the Large Astronomical Telescope, and the Tokamak, among others.
b) *Public experimental platforms* (PEPs) serves basic research, applied fundamental research and applied research for multiple disciplines. PEP development usually depends on D-RIs and can be considered the evolutionary result of D-RIs. For example, the Radiation Synchrotron, which was developed based on the radiation light of the Collider, has a wide range of application areas and direct social and economic influence. Other typical PEPs include the Spallation Neutron Source and the High Magnetic Field Facility.
c) *Public infrastructures* (PIs) are designed to provide scientific data and information for national economic development, national security, and social development and research in related subjects. Their emphasis on public service in scientific activities reflects the social function of the scientific effects of the PI. Some examples of PIs include the time service system, remote sensing satellites and aircraft, and space weather monitoring stations, among others.

3.2. Dimensions of scientific effects

This paper broadens the scientific perspective of RIs and identifies four aspects of RI scientific effects, including science and technology (S&T) advancement, the capability cultivation effect, the networking effect and the clustering effect (see Table 3). Among these scientific effects, the S&T advancement effect is prominent. The capability cultivation effect includes various impacts on RI laboratory and research organizations. The networking effect and the clustering effect are the results of the complexity and public goods characteristics of RI.

The four types of effects shown in Table 3 can be divided into two categories based on whether the specific effect is directly scientific or systematic. The first group consists of direct or non-discretionary outcomes, and the second group consists of more systematic or discretionary outcomes (see Fig. 1); in the second group, the relevant effects will not be realized unless managers/administrators actively advocate for them and allocate the required resources to achieve them (GSF, 2014). However, the first group of effects will not emerge automatically and efficiently. Thus, the key points of policy instruments directed towards the two groups should be different.

Table 3
The analytical dimensions of RI scientific effects.

Effect perspective	Definition	Relevant literature	Group
S&T advancement effect	To advance the depth and coverage of science and technology	EC (2010); Zuijdam et al. (2011); GSF (2014); CAS (2007)	Directly scientific
Capability cultivation effect	To develop top level science organization and to absorb or cultivate top level talent; to train scientists, engineers, administrators, and other professionals	GSF (2014); Zuijdam et al. (2011); CAS (2007)	
Networking effect	To develop networks with relevant RI users or co-builders and other stakeholders	Zuijdam et al. (2011)	Science-based systematic
Clustering effect	To interact with academics as well as industries located nearby and to form a knowledge ecosystem	OECD (1999), (2001)	

Source: Authors' elaboration.

4. A cross-case comparative evaluation of scientific effects

For each functional type of RI, 3 typical cases are chosen based on the availability of data. Consequently, 9 cases in total are selected, as shown in Table 4. These selected RIs are typical, and they cover different disciplines and research areas. Moreover, the different operation periods of different RIs has also been considered in this paper. To be specific, the 9 cases are the Beijing Electron Positron Collider (BEPC), the Beijing Synchrotron Radiation Facility (BSRF), the Experimental Advanced Superconducting Tokamak (EAST), the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST), the Shanghai Synchrotron Radiation Facility (SSRF), the Steady High Magnetic Field Facility (SHMFF), the Meridian Space Weather Monitoring Project (Meridian Project), the BPL and BPM Time Services Systems (BPL & BPM) and the "Shiyan 1" Research Vessel (Shiyan 1). Basic information about these RI cases is listed in Table 4.

The function of an RI is connected to the discipline it serves. For example, RIs are a necessary support tool in some research fields, such as the BEPC in particle physics, LAMOST in astronomy, as well as EAST in nuclear physics. These are D-RIs, which are usually related to some specific discipline. In contrast, PEPs can provide support for multiple disciplines. For example, material science and structural biology depend on the SSRF or the SHMFF. PIs provide research for or devote attention to the public function of scientific effects. In earth science and environmental science, the Meridian Project provides space weather data, the Shiyan 1 (research vessel) provides the sailing capability to collect deep sea data, and BPL & BPM provide time service for various scientific and economic sectors.

4.1. S&T advancement effect

Currently, RIs are crucial to the advancement of science in nearly all scientific fields and have become an indispensable tool for many disciplines (ESFRI, 2011). With regard to the problem of how to demonstrate this contribution, it is well-acknowledged in "facility metrics" studies that the standard performance indicators do not account for the complexities of RI output (Heidler and Hallonsten, 2015). Tallies of traditional publications and patents are used to evaluate R&D output, although there are many problems with this approach. In this article, the numbers of paper publications, paper citations, and patents that are issued under the support of the case RIs are reported in Table 5.

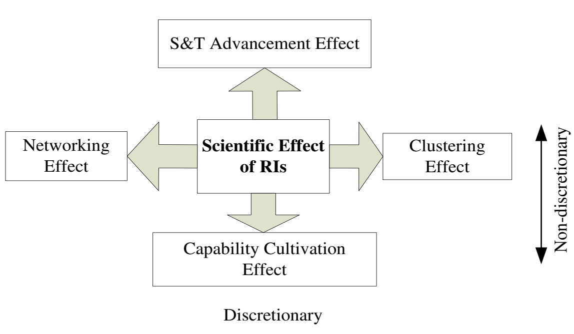

Fig. 1. An analytical framework of RI scientific effects.

Based on the publication data over time, we can observe that RI paper publications generally increase each year with some discontinuity. However, we also observe that the scientific output of different types of RIs differs in terms of the amount. The number of papers published by the PEPs and the D-RIs is relatively larger than that of the PIs. Because more paper publications are a proxy for a comparably greater capability for knowledge production, the former two types of RIs are more reminiscent of a science tool, and they should be evaluated by the scientific community in terms of their focus on supporting user experiments and fulfilling scientific objectives. Of these two types, PEPs promote multi-disciplinary development as well as the blending of different disciplines, which may lead to more top publications. However, PIs may have fewer papers published because public service is their direct and primary goal.

In terms of the cost of publications, some claim that the scientific research conducted by RIs is quite expensive because the average cost of a single journal publication may easily reach hundreds of millions of dollars (Hallonsten, 2014). This seems to be true. However, the hybrid fields supported by RIs are especially valuable for the growth of science. Meanwhile, RIs produce reorganized knowledge that stimulates the whole system (Hallonsten and Heinze, 2013) and contributes to solving "grand challenges" and other inherently interdisciplinary issues (Heidler and Hallonsten, 2015).

In addition to publications, citations and patents are also useful indicators of RI knowledge output. However, as we can see from the annual report data in Table 5, the citation data of Chinese RIs may be unreliable and sporadic. Additionally, few authorized patents can be observed, and the number of patents did not increase considerably over the analyzed years. This is because quantitative evaluation is not the primary measure of RI performance used by the Chinese management authority. Additionally, open access is a customary principle and usual practice of RIs. Consequently, the technology publicity gained through international conferences and seminars is a form of technology output from RIs. We can see that EAST is an exception compared with other case RIs in terms of patent numbers. EAST has more patents than the other RIs, which is probably due to its deep involvement in and in-kind contributions to the ITER (International Thermonuclear Experimental Reactor) project.

Because traditional bibliometric measures may not present the full picture of RI scientific performance, one direct method of measuring the importance of RI research performance is the frequency with which RI studies are included in China's annual top ten Science and Technology Progress list, a highly influential ranking made by expert scientists (see Table 6).

The following aspects can be observed from Table 6: Firstly, RIs have had prominent achievements throughout their lifecycles. They do not wait until they begin operating to become scientifically productive, and, in fact, the construction of RIs is often accompanied by major breakthroughs in science and technology. Secondly, the highest level

Table 4
Descriptive information for nine typical RI cases in China.

Classification	Name of RI	Construction and Operation Institute	Discipline	Year of Operation	Investment (million RMB)	Location	Operating Conditions and Features
D-RI	BEPC	Institute of High Energy Physics (IHEP)	Particle Physics	1990	240	Beijing	Total operation hours, 7348
	EAST	Institute of Plasma Physics (IPP)	Nuclear Physics	2007	99	Hefei	Total operation hours, 3512
	LAMOST	National Astronomical Observatories (NAOC)	Space and Astronomy	2011	235	Hebei	Released 1,558,924 spectra distributed in 738 sky areas
PEP	BSRF	Institute of High Energy Physics (IHEP)	Material/Accelerator Science	1990	Within BEPC	Beijing	No. of users, 1528; No. of users' research tasks completed, 630
	SSRF	Shanghai Institute of Applied Physics (SINAP)	Material/Accelerator Science	2009	1435	Shanghai	No. of users, 2486; No. of users' research tasks completed, 1185
	SHMFF	High Magnetic Field Laboratory (CHMFL)	Material	Trial operation from 2010	–	Hefei	No. of users' research tasks completed, 304 (data from SHMFF)
PI	Meridian Project	National Space Science Center (NSSC)	Space and Astronomy	2011	167	Distributed	Data file storage, 1.87 TB
	BPL & BPM	National Time Service Center (NTS)	Engineering Science	1960s & 1970s	–	Shanxi	Broadcast hours of BPM, 26,824.9; of BPL, 8736.3
	Shiyan 1	South China Sea Institute of Oceanology (SCSIO)	Earth Systems	2009	–	Guangdong	Task hour, 208; days sailing, 28,961 mails

Source: Chinese Academy of Sciences Large Research Infrastructures Annual Report 2013.
Note: The sign "-" means the unavailability of data.

of progress includes not only the completion of new RI construction but also the achievement of key nodes of projects and upgrades. Thirdly, user achievement has become increasingly prominent in recent years, especially in fields, such as structural biology and catalyst using light source facilities. What is more, this also provides evidence regarding the high capability of PEPs to serve as efficient scientific tools. We can also observe that an RI, such as the SSRF or the BEPC, can be listed as among the top science and technology progress recipients many times, which illustrates their significant contributions.

In summary, RIs serve as an important scientific tool for providing public knowledge. They are an indispensable tool for the development of some disciplines. As Stokes (1997) has noted, many of the structures and processes of basic scientific exploration can be revealed only by technological achievement, and science exists only if the technology exists in these cases. Due to the enlarged research scale and focused, innovative research activities, both the construction and operation stages of RIs have yielded great scientific and technological progress. Additionally, these large facilities promote scientific progress, while the progress of science requires even more from them, which in turn promotes their further development. Among the three RI types, D-RIs and PEPs have a greater capacity for knowledge production, while PIs are characterized by their provision of scientific services.

4.2. Capability cultivation effect

The construction and operation of effective and timely RIs is an important part of building research capacity (EC, 2010). Currently, research activity is becoming more multi-disciplinary and interdisciplinary, and the complexity of scientific and social issues makes them impossible to solve from a single-disciplinary perspective. At the same time, RIs are needed to achieve a scientific goal in a given time or to provide a platform for multi-disciplinary research. What is more, RIs not only play an important role in acquiring new knowledge but also in providing a more effective means of conducting multi-disciplinary scientific

Table 5
The knowledge output of the RI cases.

	Indicator	D-RI			PEP		PI		
		BEPC & BESF	EAST	LAMOST	SSRF	HMFF	Meridian Project	BPL & BPM	Shiyan 1
2008	Publications	215	42	18	–	–	–	5	–
	Citations	345	118	20	–			0	
	Patents	5	16	3	–			12	
2009	Publications	249	80	6	12			8	
	Citations	409	–	27	–			28	
	Patents	8	23	–	–			–	
2010	Publications	203	106	12	101			4	20
	Citations	226	–	32	–			30	59
	Patents	7	18	–	–			3	–
2011	Publications	244	109	9	261	69	54	8	1
	Citations	372	–	22	–	–	156	32	2
	Patents	9	17	–	1	–	3	7	–
2012	Publications	226	99	19	315	95	58	5	6
	Citations	–	–	57	–	–	322	40	9
	Patents	15	18	–	1	3	5	8	–
2013	Publications	233	151	28	455	103	73	12	4
	Citations	–	–	68	–	81	412	42	–
	Patents	–	15	–	5	8	2	7	12
2014	Publications	333	208	17	506	122	102	13	17
	Citations	49	–	11	–	84	412	20	–
	Patents	2	26	–	5	3	2	8	–

Publications: Papers collected by SCI. Citations and patents represent patents for inventions.
Source: Chinese Academy of Sciences Large Research Infrastructures Annual Report 2008–2014.
Note: The sign "-" indicates the data were unavailable.

Table 6
Frequency of top 10 science and technology progress awards among RI cases in most recent 10 years.

No.	Impact	Content of Progress	Property
1	China's Top 10 S&T Progress 2014	Resolving the crystal structure of anthropogenic glucose transporters GLUT1 and preliminarily revealing its working mechanism and relative pathogenesis of disease by using BL17U1 of the SSRF for the first time in the world.	User achievement
2	China's Top 10 S&T Progress 2014	Considerable breakthrough in research on the highly efficient conversion of methane using the SSRF X-ray absorption fine structure spectrum station BL14W1.	User achievement
3	China's Top 10 S&T Progress 2009	Completing the construction of the SSRF, China's largest scientific platform and one of the world's best performing 3rd intermediate energy light sources at present, with a total investment of 1.24 billion.	New construction
4	China's Top 10 S&T Progress 2008	Completing the major upgrade of the BEPC; after 17 years of operation, China has invested RMB 640 million to-date, laying the foundation to maintain a leading international position in high-energy research.	Upgrade
5	China's Top 10 S&T Progress 2008	Completing the construction of LAMOST, the world's largest diameter wide-field telescope, with a total investment of about RMB 235 million.	New construction
6	China's Top 10 S&T Progress 2006	Completing the construction of EAST, which is known as the "world fusion energy development milestone", with a national investment of RMB 165 million, denoting China's position as an international leader in fusion research.	New construction
7	China's Top 10 S&T Progress 2006	Breakthrough of the BEPC II upgrade project; storage ring achieved beam accumulation, storage ring and linear accelerator working stably, and beam performing well, indicating that the goal of the second phase of the BEPCII construction task has been met.	Key node of project

Source: Data collected by the author from public information.

research. This can be attributed in part to the RI selection mechanism, in which only the most outstanding research groups have access to the research opportunities provided by RIs. Therefore, one important aspect of RIs is their effect on the reputation of research groups, organizations and fields (Zuijdam et al., 2011).

An organization is consciously established with a formal structure and a clear purpose (Edquist and Johnson, 1997). As institutional innovation has become a precondition for knowledge innovation and leap-forward development, the efficient knowledge organization and operation mechanisms are the key to knowledge growth. The construction of a novel organization or mechanism, such as a big-science center (BSC), within an RI is very important. Housing BSCs inside traditional national research institutions or universities (Constructor & Operator Institute, COI) has been a common practice in China. BSCs tend to be stable research organizations with fixed modes of management, including various stakeholders, an evaluation model, ownership, a cost model, and infrastructure availability. These self-organizing and self-value-added properties allow BSCs to operate independently with public financial support, without having to rely too greatly on COI's allocation of resources and tasks. Typically, RIs offer a research opportunity to a BSC, which makes the BSC the focus of international communication and cooperation, as well as a gathering place for talent.

Chinese national authorities identify several BSCs as National Laboratories (NLs) and National Science Centers (NSCs) for the purpose of ensuring the effective operation and scientific productivity of RIs. The organizational system of some of the RI management cases in which the RIs have NL or NSC authorization is shown in Fig. 2.

NLs and NSCs have the capability to transcend organizational needs by responding to national needs, providing the assurance of high-quality research resources. To achieve magnificent scientific achievements, NLs and NSCs are gradually developing and completing the knowledge innovation system, which includes the management of RIs, the establishment of internal and external organizations, the construction of knowledge innovation mechanisms and cooperative innovation.

The mechanism of a BSC is different from that of a traditional science institute. The reliable operation of an RI provides guarantees of stability and sustainable development for the top level science research activities of a BSC. BSCs coordinate with other scientific and technological areas and provide scientific services for different disciplines, among other activities. This is the advantage of a BSC's mechanism.

In addition to organizational development, training researchers and engineers through their experience with RIs is an integral part of the research capacity building process (EC, 2010). A BSC's successful operation and research rely on staff who absorb new knowledge to advance the frontiers of science and technology research. The personnel and education characteristics of the analyzed RIs are listed in Table 7.

Personnel structures vary among the different stages of RIs. According to their position, RI staff can be classified into two categories, i.e., operational and maintenance personnel and experimental researchers, which reflect the missions of the following RIs: operations and experimental research. These missions play different roles during different stages of RI operation. At first, during the trial operation, an RI is somewhat similar to a traditional research institute in which relatively fewer operational and maintenance personnel are needed, such as the SHMFF. Nevertheless, as the RI lifecycle progresses, the number of operational and maintenance personnel increase to many times that of the experimental researchers in most of the RI cases. However, in the mature stage of operation, the numbers of the two types of personnel become roughly equal, as in the case of the BEPC, or the boundaries between the personnel types blurs, as in the case of BPL & BPM. Researchers perform both types of missions, hence receiving first-hand experience from an experimental viewpoint and using their theoretical knowledge to provide assistance for the experiment. However, this attribute of RI personnel is generally not recognized by

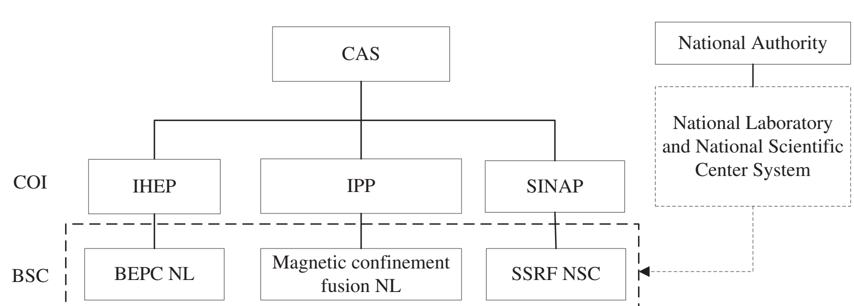

Fig. 2. The management organization framework of some RI cases Source: authors' elaboration.

Table 7
Cultivation of scientific and technological teams and talent among the RI cases (year 2014).

RI	No. of staff.	Classified by position			Talent cultivation	
		Operational & maintenance personnel	Experimental researchers	Others	Graduate students	No. of postdoctoral scholars at research centers
BEPC & BSRF	395	191	166	38	184	5
EAST	346	277	51	18	325	3
LAMOST	54	49	5	22	1	54
SSRF	428	365	46	17	112	5
SHMFF	169	48	99	22	102	12
Meridian Project	292	204	52	36	126	20
BPL & BPM	153	147		6	145	2

Source: Chinese Academy of Sciences Large Research Infrastructures Annual Report 2014.

Chinese academics. Conditions, such as a lack of channels for promotion, less recognition compared with that given to other academic personnel and other problems, have made it difficult to attract and retain essential RI personnel.

RIs also contribute to science education in the frontiers of experimental science, which can be observed from Table 7. One important principle used to assess the fundamental research of the US National Science Foundation is the combination of education and research. In the BSC context, access to and use of these technologically well-equipped RIs enables young researchers and students to tackle problems among high-level interdisciplinary teams, provides them with excellent qualifications for tasks in science and develops their career mobility.

From an external perspective, RIs and BSCs are noted for attracting top-level talent. These organizations give capable and well-trained scientists the opportunity to focus on fundamental research that is subsidized by the public, which contributes to "brain circulation" and reduces the risk of "brain drain" for the organization. At a higher level, this concept offers a basis for implementing public policies within regions or countries (EC, 2010).

In summary, RIs, with the big-science mechanism, contribute to the building of research capacity and the enhancement of certain research areas. Moreover, RI organizations with nationally-authorized institutes, such as NLs or NSCs, help to build an RI's capacity and promote its future development. With respect to the personnel issue, the personnel structure evolves in different stages of an RI's operation. The featured personnel are of great significance to the maintenance and good scientific output of an RI, although it is hard to evaluate the added value of their work. More importantly, RIs also play a significant role in science education, as they provide opportunities for graduate students to move closer to the frontiers of science and technology.

4.3. Networking effect

The involvement of the various scientific stakeholders of RIs creates a networking effect. Networking has become common over the last 20 years (Powell, 1990; Rosenbloom and Spencer, 1996; Roberts and Liu, 2001; Chesbrough, 2003). There are, of course, distributed RIs, such as the Meridian Project, where the project's technological assets are distributed among several locations and the physical form of the RI is a network. However, for most RIs, the network is more of invisible scientific interaction among organizations, including interactions based on formal contracts and less formal relationships among users and the scientific community. According to the actor-network theory, scientific activity is network of interactions among humans and non-human objects (Michel, 1986; Bruno, 1987, 1988; John, 1987). RIs are an indispensable non-human tool and must interact with human power so that they can play a role. Moreover, the diversity of network members can help partners gain extensive knowledge. As mentioned above, there are several stages in the lifecycles of RIs. The network mechanism of the construction stage and the operation stage co-evolves with the development of RIs.

RIs serve as "nuclei" for the formation of skills and knowledge, either through the centralization of such skills or via the networked collaboration among researchers by highlighting multi-disciplinary teams (EC, 2010). The domestic knowledge network of the SSRF in the construction stage is shown in Fig. 3. The construction stage consists of three parts, i.e., capital construction, facility design and facility manufacturing. Consequently, the network partners can be divided into three groups as follows: architecture construction companies, the design and manufacturing institutes of CAS and the private component manufacturers. During the co-design and procurement stage, all of the three groups contribute to knowledge innovation in different ways. In terms of general high-performance components, the SSRF benefits from cooperation with a small group of high-tech companies and from those companies' experience in the military industry. The private enterprises also receive recognition from the accelerator field through their own technology R&D for the SSRF. The CAS institutes, the university and the companies undertake a large part of the R&D work for core parts of the SSRF. For example, magnets are a key component of the complex accelerators, and the University of Science and Technology of China (USTC) and IHEP, which assumes many of the magnet development tasks, provide valuable resources and experience through their construction of the first and second generations of the light source. The SSRF benefits from networking with USTC and IHEP and compensates for its lack of experience in building a large light source.

In the operation stage, the supply chain network still exists due to the RI's need for maintenance and updates. Nevertheless, the main actors within the network have become the scholars of the academic institute and the form of the network has become invisible. Relative to this invisible network, Crane (1972) studies how knowledge grows and how the scientific community affects the spread of knowledge. The amount and degree of research collaboration can be investigated based on the number of co-authored articles (Newman, 2003). In addition, David (2001) notes that the free sharing of knowledge in the scientific community is the main driver of academic innovation. Taking the SSRF as an example, 132,758 h of user machine time have been provided by the seven beamlines from the start of operations in 2009 to 2013. Furthermore, 1403 research groups from 310 institutes, consisting of 18,137 person-hours and a total of 7228 people, have carried out experiments. According to the user source, 49% of users are from universities, 34% are from research institutes, 11% are from enterprises and 6% are from hospitals. Some of the users have built cooperative organizations with SINAP (the operator of the SSRF), while some have established cooperative beamlines on the SSRF.

Based on the classification of key stakeholders involved in big-science research (Autio et al., 1996; Vuola and Hameri, 2006), stakeholders are divided into the following three categories in this paper: academic, industrial and public stakeholders. The network mechanism of these construction and operation stage stakeholders is explained in Table 8.

In summary, the networking effect is an important mechanism through which RIs interact with industries and academics and increase cooperation in science and technology activities. Formal and informal social networks and shared values and mutual trust are established

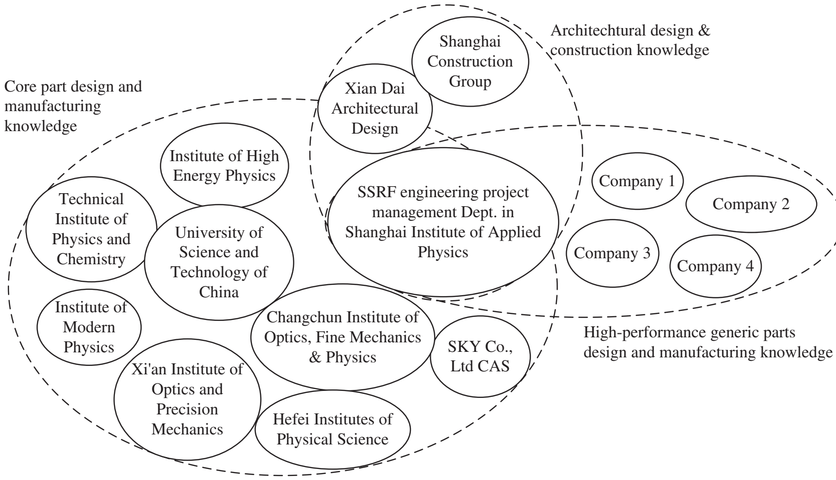

Fig. 3. The domestic knowledge network of the SSRF in the construction stage Source: authors' elaboration.

among the partners. In this paper, the network effects of RIs at the construction and operation stages are illustrated. In the construction stage, the network serves as a supply chain network formed by the contractual relationships among partners, while RIs act as the “launching customers” for innovative products and services provided by the commercial sector (Zuijdam et al., 2011). In the operation stage, RIs provide services for a wide range of scientific communities and jointly carry out scientific research activities. Thus, they are akin to an invisible college. Moreover, multi-disciplinary scientific users communicate through user meetings and the shared use of RIs to cooperate and share information. Therefore, as the RI stages progress, the degree of cooperation, purpose and depth of the network also changes from recurrent and dense connections among a fairly closed group with a clear purpose to open, episodic or fluid networks (Granovetter, 1985).

4.4. Clustering effect

The co-location of RIs has become a common phenomenon. Scholars have studied technology clusters, knowledge clusters, and innovation clusters (Ibrahim and Fallah, 2005; Liyanage, 1995; Hans-dieter, 2008), all of which exhibit agglomerations of organizations, such as universities, research institutes, think tanks, government institutes, and knowledge-intensive companies, and form geographically proximate networks. The spatial landscape of RIs in Europe shows that science and technology clusters are often co-located with RIs (EC, 2010). For the sake of cost efficiency and knowledge production enhancement, a cluster of RIs in the same area is needed. Through the attraction of high-tech companies, specialized facilities, and educational establishments and the potential for new employment possibilities, an “innovation biotope” is created by RIs in their regions (EIROforum, 2014). The scientific outputs serve as important inputs to the innovative activities of firms (Motohashi, 2006) and the science-industry linkage is an important factor for the economic performance of nations (Freeman, 1991). Particularly in the mature phases of technological progress, an RI community may extend to include clusters of networks or even broad collections of social institutions (e.g., education systems, legal regimes) at the level of the national innovation system (Lynn et al., 1996). According to Pavitt's (1984) industry classification, RIs may play a more important role in science-based industries than in other industries. For example, the pharmaceutical industry and mobile communications industry are typical science-based industries, in which science serves as an innovation source. Moreover, “inside” research within public research institutions and universities plays a significant role in innovation (Motohashi, 2009). Because RIs are at the very heart of the knowledge triangle of research, education and innovation, an RI cluster forms a large knowledge system that comprehensively supports the knowledge flow or “brain circulation” of academics and industries, and in a large sense, the nation and society. Geographic proximity is of great importance in supporting the production, identification, appropriation and flow of tacit knowledge. Thus, the knowledge ecosystem of an RI cluster is formed (see Fig. 4).

The trend towards RI clustering can probably be attributed to the following reasons. Firstly, some RIs normally coexist with each other due to the homogeneous nature of their disciplines. For example, the structural biology center is usually located near the Synchrotron Light

Table 8
Mechanism of RI networking effect.

Stage	Stakeholder		
	Academic stakeholders	Industrial stakeholders	Public stakeholders
Construction stage	Cost efficient due to the high performance of technological solutions; Access to other unknown new technologies; Better performance of solutions or radically new solutions to scientific instruments.	Active technological scanning to long-term supply contracts; Access to non-cost knowledge networks; Spin-offs from contract work; Upgrade of skills and potential for the emergence of new technology-based industries.	Exploitation of technological spillovers; Upgrade of skill base.
Operation stage	Resulting in cost-effective, world-class research; Advanced instruments to obtain new research information; Testing existing theories; Formulating new hypotheses; Increasing the quality of scientists; Enabling and justifying challenging scientific experiments.	R&D personnel have access to a wider social and knowledge network, enabling innovation to take place and speeding up the innovation process; Technological learning resulting from collaboration; Strengthening industrial competitiveness and networking.	Enriching social network among people at big-science lab; Catalyzing national innovation; Improving national self-esteem and consciousness; Strengthening the national educational system; Integrated science, technology, and industrial policy.

Note: academic stakeholders include co-research organizations as well as user organizations. Industrial stakeholders include component manufacturers and industrial users. Public stakeholders refer to the extensive population.
Source: Authors' elaboration.

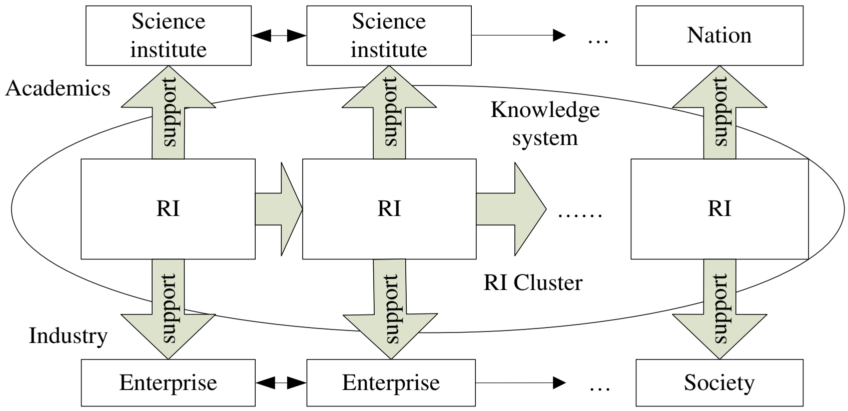

Fig. 4. The knowledge ecosystem of the RI clustering effect Source: authors' elaboration.

Source. The National Center of Protein Science Shanghai (NCPSS), which is near the SSRF, built five beamlines and six stations at the SSRF. Secondly, each RI needs a common set of facilities, such as cooling towers, low-voltage equipment and security facilities that are very expensive, and it is more efficient to share these facilities with other RIs. Thirdly, local governments have paved the way for RI clusters because regional RI clusters bring favorable economic returns to and raise the international visibility of the regions where they are located (EIROforum, 2014).

In 2014, CAS started to promote an initiative for a comprehensive research center in its Pioneer Action plan that consisted of supporting several comprehensive regional clusters or professional RI centers (CAS, 2014). The Pudong Innovation Campus of Shanghai also promoted this initiative. Public platform RIs, such as the SSRF, are at the center of an RI cluster and play a key role in the cluster. In addition to the SSRF and NCPSS, the cluster includes the Supercomputer Center, the New Medicine Center, the Shanghai Institute for Advanced Study, the Drug Discovery Research and Development Base, Shanghai Tech University, and others. More RIs are being established according to the CAS plan. Big-science research focuses on cross-frontier areas including life science, materials science, environmental science, energy science as well as matter science.

According to an interview with the SSRF, interaction and cooperation among local enterprises and spatial embeddedness are less preferred than discipline proximity. Although the literature shows that the role of the science sector in China's economic growth has become larger and the science-industry linkage is also improving due to efforts to introduce innovative policies for system reform (Motohashi, 2006), problems still exist to a large extent. As an emerging innovation system, China's innovation system, in which interactions among organizations may be still in the formative stages despite the existence of most of the system elements, may be lacking some capabilities, and there are no simple solutions to the development of those capabilities (Chaminade et al., 2009). The nature of technology needs and the market failures relating to technology efforts are different between developed and developing countries, and their innovation systems differ in some respects as well (Pietrobelli and Bellotti, 2009). As a learning model for STI (science, technology and innovation) in a developing country, the RI-based cluster is a relatively new phenomenon in China. The RI institute examples in China consist of a single discipline or only few related disciplines, and cooperation among different RI institutes faces difficulties, such as distance and available property. Therefore, looking for an overall RI location layout that co-supports adjacent RIs by building a big-science center is the policy experiment being carried out by the Chinese government to catch up to the global RI development trend. Furthermore, enhancing the interactions and coordination between RIs and enterprises may be an area of future policy emphasis to activate the innovation system.

5. Conclusions and policy implications

5.1. Conclusions

Research infrastructures (RIs) are expected to play an important role in economic and social development. This paper comprehensively evaluates the impact of RIs on scientific activities using typical Chinese cases. To achieve this research purpose, this paper proposed a multi-dimensional analytical framework for evaluating the scientific effects of RIs in terms of the S&T advancement effect, the capability cultivation effect, the clustering effect, and the networking effect. Our analytical framework can provide a comprehensive evaluation of the scientific effects of RIs in terms of their input-side, output-side, process-side and environment-side impacts on scientific activities. Based on a multi-case analysis of China's typical RIs, our quantitative and qualitative analyses have presented a range of evidence regarding the development effects of RIs in an emerging country.

Our study contributes to the literature by exploring the social value of the scientific effects of RIs, which proved that RIs are not only a scientific tool but also a social and innovation tool. Our study fills a research gap in the extant literature regarding a lack of systematic analyses of the scientific impacts of RIs. Previous studies have neglected the effect of external links to an RI's internal innovation process. Due to the large scale and long lifecycles of RIs, systematization and evolution should be included as fundamental considerations when evaluating RI activities. An RI serves as a stable and prominent research resource and thus forms new research patterns and leads to a flatter scientific organizing structure while absorbing and cultivating external talent. This paper not only examined the direct scientific effects but also explored the systematic nature of RIs. Based on an analysis of nine typical large research infrastructures in China, this paper identifies the following four types of RI science effects: S&T advancement effect, capability cultivation effect, clustering effect, and networking effect.

The classification of RIs is a useful method for in-depth research on RI effects. Previous studies have focused mainly on single RIs, and very few studies have paid sufficient attention to the cross-effect differences of RIs. This paper presents both a function-based classification of RIs and a classification of the scientific effects of RIs. No study has implemented a similar approach from an academic perspective. Specifically, we presented a classification of Chinese RIs and discussed the features of three types of RIs, i.e., dedicated RI, public experimental platform and public infrastructure. Thus, we summarize the discoveries of our multi-case study in Table 9, which displays the main findings of the paper according to the following two dimensions: the type of scientific effects versus the classification of RIs.

Table 9
A summary of RI types and scientific effects.

RI type	Effects			
	S&T advancement effect	Capability cultivation effect	Networking effect	Clustering effect
D-RI	High scientific productivity of one discipline	Predominant organization of national lab, scientific talent cultivation	Single discipline network	The core or important component of a cluster
PEP	High scientific productivity of multiple disciplines	Predominant organization of national center, scientific talent cultivation	Multi-disciplinary network	Capability for forming a cluster and being the core
PI	Scientific service instead of scientific output	Strategic resource for public needs	Single discipline or multi-disciplinary network for public objectives	Not prominent

Source: Authors' elaboration.

5.2. Policy implications

Based on our multi-case analysis of Chinese RIs and four associated scientific effects, we make several policy suggestions for the future management of Chinese RIs.

Firstly, policymakers should take into account the differences across different types of RIs according to their function and mission. Due to the variety of RI characteristics, an RI evaluation should consider not only simple S&T indicators, such as publications, citation and patents, but also extended scientific effects, such as major scientific achievements, satisfying public needs, solving major challenge and contributing to regional/national innovation systems. Of the three types, PEPs serve as a multi-disciplinary tool that has high potential for promoting scientific output, creating an impartial scientific culture and supporting a prosperous research environment. Because PEPs have a unique ability to serve as the core of a multi-disciplinary network and cluster and to serve industry, the policy emphases and specific policy directives for PEPs should be carefully designed to facilitate interactions among different disciplines and strengthen academic-industry relations. D-RIs are more focused on large scientific goals, and they engage in international cooperation to solve major scientific problems. Thus, resources and environments designed to support international science and technology cooperation should be provided so that the best talent in the field can work together towards major science objectives. Policy for PIs should focus on scientific service capability and operation status.

Secondly, the input aspect of capability cultivation building deserves more attention. Among the effects of capability cultivation building, more concern should be given to big-science organizations, scientific and technical talent, and RI institutions. Big-science organizations differ from regular research institutes or universities. With the public applications of large RIs and relatively independent operating budgets granted by the government, big-science centers form an "independent kingdom" where the mission and rules are different than those in traditional science settings. BSCs are more open and they collaborate with a wide range of external organizations. BSC activities are more technically complex, targeting major objectives that have to be fulfilled through the cooperation of talented researchers and partners. In this model, the experimental researcher with technological experience is particularly important. It is their techniques making the top brain's idea coming true through regular machine working. BSC management is more complex, and requires managers to work with different stakeholders and balance different values. In summary, the capability of RIs refers to both technical and managerial perspectives. Specific regulations should be made to ensure that RIs have a sufficient supply of resources, including training in managerial skills and the appraisal of specific skills and personnel performance, to promote further RI development and the growth and efficiency of the whole science sector.

Thirdly, the building of the networking capability of RIs should receive attention so that social capital can catalyze learning processes and knowledge-sharing among stakeholders. Typically, openness and cooperation among industries related to RIs are viewed as secondary to the science mission. However, with the development of industrial innovation capacity as well as positive experiences with technology transfers based on US and European practices, there should be more emphasis on Chinese RIs' involvement in industry and on technology transfer policies. Additionally, the administrative structure of RI organizations needs to be flexible to adjust to networking needs. Various functions of RI organizations, such as user management, operations management, machine research, and scientific research should be carefully investigated in terms of their dynamics and mechanisms to determine whether to structure them as legal entities or unincorporated units. The structure of RI organizations should also be carefully designed regarding whether to establish a nimbler structure or a comprehensive integrated structure. These decisions may depend on the disciplines of the RIs and the RIs' natural physical forms, as well as other intrinsic factors of specific RIs.

Although the paper conducted some exploratory work regarding scientific effects based on data obtained for Chinese RIs, research on this topic is still insufficient and there are limitations to this study. For example, some data are lacking for quantitative analysis. The aspects of scientific effects may be incomplete and the logical relationship requires further interpretation. An international comparison of RI scientific effects would be helpful in better understanding the development problem and policy points for Chinese RIs, but these comparisons are only partially attempted in this paper. Thus, further research could provide more empirical evidence and more data for quantitative research. Moreover, a possible interesting development of this paper could be to link the literature of RIs with the literature of national innovation systems, which has also been recently developed for emerging countries, particularly for China (see, for instance Pietrobelli and Bellotti, 2009; Motohashi, 2006, 2009; Motohashi and Yun, 2007; Chaminade et al., 2009). An extension of this paper would be valuable in presenting more systematic evidence of the contributions that RIs make to the development of the Chinese national innovation system. Because RIs operate as specific research organizations or platforms within national innovation systems, their impacts cannot be separated from the embedded effects of the elements of national innovation systems.

Acknowledgments

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