[Forthcoming in Research Policy]

International Research Collaboration: An Emerging Domain of Innovation Studies?

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Abstract

International research collaboration (IRC) has been increasingly important as an emerging area of innovation studies. This study reviews the intellectual base, main research trajectories and intellectual communities of the IRC research domain over the period 1957-2015. It integrates qualitative review and three quantitative analyses including co-citation network analysis, main path analysis and bibliographic coupling analysis. The results show that the IRC research has gone through three phases, namely, "emergence" (1957-1991), "fermentation" (1992-2005) and "take-off" (2006-2015) phases. The co-citation network analysis confirms that the IRC research field has been developed under the influence of two pioneering studies related to bibliometrics research. The main research trajectories in IRC studies over its three development phases and over the whole period are identified based on the main path analysis, which shows that co-authorship analysis is the main research method in IRC studies. A bibliographic coupling analysis suggests that the whole IRC research domain can be classified into five distinct intellectual areas: drivers of IRC, IRC patterns, IRC effects, IRC networks and IRC measurement. Seven topics for future research are also identified.

Keywords: International research collaboration; Evolution and future research agenda; Co-citation network analysis; Main path analysis; Bibliographic coupling analysis

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1. Introduction

In the context of "Big Science", research collaboration (the various forms include collaboration between individuals, groups, departments, institutions, regions and countries) is a growing phenomenon, which has attracted the attention of many scholars (Doré et al., 1996; Georghiou, 1998; Glänzel, 2001; Luukkonen et al., 1992; Niu, 2014; Wilsdon, 2011). With an expansion of the literature on research collaboration (RC), there have been several systematic reviews of this expanding research domain (eg., Katz and Martin, 1997; Bozeman and Boardman, 2014; Subramanyam, 1983). Previous RC reviews have identified several clusters of RC, ranging from inter-individual RC through inter-departmental and inter-institutional to the international one. It should be noted that an important subset of RC, namely, international research collaboration (IRC), has become one of the hottest topics in recent years (Wang et al., 2014).

Driven by increasing global competition and rapid technological changes, more and more countries have deemed the science and technology (S&T) collaboration across countries as a critical way to foster and maintain their global innovation competitiveness (Glänzel, 2001; Hwang, 2007). A country with more collaborative linkages with other countries is placed in an advantageous position, which endows the country with privilege to leverage the domestic S&T capabilities and exploit the foreign investments in Research and Development (R&D) (Wagner, 2009). Thus, IRC has been perceived as a dominant driving force for promoting S&T advancement (Wang et al., 2014), industrial innovation and economic growth (Sharma and Thomas, 2008). Moreover, in the modern S&T domain, the increasing complexity and the growing scale of research projects, especially those that are set up to address important global challenges (e.g., energy crisis and climate change) and fundamental scientific issues, are always beyond the capabilities of an individual country (Cronin et al., 2003). As argued by Katz and Martin (1997), more and more policymakers in different countries have listed the IRC on their top agendas and adopted various measures to support IRC activities.

In this context, there has been a considerable interest in IRC research (e.g., Georghiou, 1998; Glänzel, 2001; Niu, 2014; Doré et al., 1996; Wilsdon, 2011; Luukkonen et al., 1992). IRC, as a subdomain of the broader collaboration research and policy landscape, attracted scholars' attention at least half a century ago. The first IRC publication appeared in 1957 (i.e., Watt, 1957). Since then, the literature has steadily increased and today there is an abundance of studies on IRC. Some publications examined the factors that triggered research collaboration across countries (e.g., Luukkonen et al., 1992; Adams, 2012; Beaver and Rosen, 1979; Plotnikova and Rake, 2014; Zhao et al., 2013), some researches explored the IRC structures and dynamics (e.g., Garg and Padhi, 2001; Schubert and Braun, 1990; Leclerc and Gagné, 1994; Narin et al., 1991) and some scholars investigated the IRC effects (Schmoch and Schubert, 2007; Sooryamoorthy, 2009; Tang, 2013).

A dramatic growth of IRC studies makes it necessary to review this research field as a systematic review is conducive to comprehensive understanding of a particular research domain (Martin, 2012). In addition to this important phenomenon which has important policy and practical implications, there are distinctive characteristics of IRC which differs from domestic RC which requests a full understanding of IRC as a field. The geographic, linguistic, political, cultural distances/gaps in the context of IRC are more significant than those in other kinds of RC (Fu and Li, 2016). As a result, IRC meets more challenges compared with other kinds of RC. Moreover, the stage of development of an economy also influences the capabilities and motivations for IRC. All these may affect the pattern and effects of IRC. Such differences may be slightly less significant between industrialized countries, but more pronounced when research collaboration now expands to that between East and West, and between the industrialised North and the developing South. Therefore, the patterns, processes and effects of IRC demonstrate some unique features which are not analysed in other RC studies. However, to the best of our knowledge, no systematic overview of this expanding research domain has been found in existing literature so far. As a result, we still have an incomplete understanding of the history, current state and future research trends in the IRC research field.

This paper carries out a systematic and comprehensive overview of the literature concerning IRC. Specifically, the intellectual base, the main research trajectories and the intellectual communities in IRC research field during the period 1957–2015 are systematically reviewed in this paper. Three quantitative techniques, namely, co-citation network analysis, main path analysis and bibliographic coupling analysis, are employed. It aims to provide important insights into this research field as well as the directions for future research.

This study contributes to existing literature as follows. Firstly, this paper, to our knowledge, is a first attempt to survey the IRC research field by using quantitative methods. There is a substantial body of IRC publications, yet no study has presented a systematic and comprehensive view of this research field. To fill this research gap, this study conducts a citation-based analysis to comprehensively explore the intellectual base, main research trajectories and core themes in this research field. Secondly, we demonstrate an alternative way of reviewing a research domain from a novel perspective, different from existing narrative reviews. In our study, we investigate the IRC research field by integrating three quantitative analyses (i.e., co-citation network analysis, main path analysis and bibliographic coupling analysis), which enable us to quickly grasp the knowledge structure of a large research domain, as a dramatically growing body of works may pose challenges for a comprehensive and critical review of a research field. Thus, our composite and coherent methodology can complement traditional qualitative methodologies on a literature review and is

feasible for handling a large dataset of a target field. Thirdly, based on a large sample of IRC studies, we introduce a bibliometric approach to give a comprehensive overview over the IRC research field. Hence, our study has an advantage over the traditional literature review which is largely based on small sample research or uses single quantitative method. Finally, although the quantitative method has been employed by more and more review studies, it should be noted that some quantitative review studies only rest on description of statistical data instead of giving an in-depth theoretical analysis of a particular research domain. Our study is different from traditional bibliometric research, as we seek to present a literature review that makes deep engagement of the theory, methods and findings of the papers instead of only present statistical data. Specifically, we attempt to dig through IRC histories based on a theoretical interpretation of core publications, mainstream research trajectories and intellectual communities in the IRC field.

The remainder of this study is organized as follows: the methodology employed by our study and the data search strategies are presented in Section 2. In the Sections 3, 4 and 5, we construct a systematic overview of IRC studies by detecting the intellectual base, research main paths and intellectual communities (categories) step by step. We give an agenda for future research in Section 6, and Section 7 summarizes our research findings and the implications for theory and practice.

2. Methodology and data

2.1 Methodology

Since citations in publications contain rich information on how knowledge disseminates or flow (Chen et al., 2013), the citation-based analysis has been widely accepted for reviewing the intellectual structure and evolutionary trajectories of particular research domains (e.g., Feng et al., 2015; Bhupatiraju et al., 2012; Have and Rubalcaba, 2016). This study combines three types of citation-based techniques used by previous studies (Bhupatiraju et al., 2012; Feng et al., 2015; Have and Rubalcaba, 2016), namely, co-citation network analysis[1], main path analysis[2] and bibliographic coupling analysis[3], to construct a systematic overview of IRC studies. These three quantitative analyses are introduced simultaneously to compensate for the weakness of each individual analysis, thus ensuring that a particular research domain is investigated effectively and comprehensively.

Besides, the co-citation network analysis, main path analysis and bibliographic coupling analysis are implemented with the assistance of CiteSpace, Pajek and Gephi software. These complementary visualization techniques have improved our capabilities to efficiently review IRC studies. This

[1] Please refer to Feng et al. (2015) and Lu et al. (2012) for more details on co-citation network analysis.
[2] Please refer to Bhupatiraju et al. (2012), Lu et al. (2012) and Lu et al. (2016) for more details on main path analysis.
[3] Please refer to Boyack and Klavans (2010) and Have and Rubalcaba (2016) for more details on bibliographic coupling analysis.

cannot be realized by most of the current review papers using the traditional narrative methods. More importantly, these three quantitative analyses ensure that our overview result is replicable and transparent. Thus we believe that the three quantitative analyses used in our study are promising and will be widely used for future review studies. These three quantitative analyses proceed as follows:

Firstly, co-citation network analysis is used for investigating the intellectual base of IRC studies. Co-citation refers to the correlation between the documents that are cited together by the same literature (Small, 1973). Since the co-citation network analysis is one of the most common and efficient tools that can accurately characterize the structure of the intellectual base (Small, 1973), existing literature has adopted this method to review the intellectual structure of particular scientific fields and their development over time (e.g., Feng et al., 2015; Wei et al., 2015; Chen and Guan, 2011). In this study, we follow the prior research and apply co-citation network analysis to examine the temporal structure of IRC studies. In particular, the linkages of cited articles (i.e., reference) constituting the intellectual base of this research domain are investigated with assistance of CiteSpace software.

Secondly, we follow Bhupatiraju et al. (2012) and identify the main research trajectories in IRC studies based on the main path analysis. This citation-based method was first introduced by Hummon and Dereian (1989) and later extended by Verspagen (2007), and it offers an important algorithm to seek the citation links with the highest value of search path count (SPC[4]). In fact, the SPC value is the amount of times the citation link has been traversed if one exhausts the search from the starting nodes to the ending nodes (Chen et al., 2013; Chuang et al., 2014). As Lu and Liu (2014) noted, the higher SPC value of the citation link indicates the more crucial role it plays in driving knowledge diffusion. So, we can trace the main research trajectories in a particular research field with the assistance of the main path analysis. To date, current studies have introduced some algorithms for identifying the main research trajectories, including local main path, global main path and key-route main path (Liu and Lu, 2012). It should be noted that both the local and global main paths are subject to a critical limitation that not all of the links having the highest SPC value can be identified by these two algorithms. The key-route main path[5] can cope with this limitation (Liu and Lu, 2012), and thus we employ the key-route algorithm to reveal the main knowledge diffusion within IRC studies.

Thirdly, we follow previous studies (e.g., Have and Rubalcaba, 2016) and apply the bibliographic coupling method (Kessler, 1963) to detect the intellectual communities in the IRC research field. This method is applied to sort out the literature that cites a group of same references, as it is based on

[4] Please refer to previous studies (Liu and Lu, 2012; Liu et al., 2016; Liu et al., 2013) for more detail on how the SPC value is calculated.

[5] Please refer to previous studies (Chuang et al., 2014; Chen et al., 2013; Hung et al., 2014; Liu and Lu, 2012) for more detail on how the key-route main path is constructed.

the assumption that the documents sharing the same set of references are more similar to each other (Have and Rubalcaba, 2016). Boyack and Klavans (2010) showed that the bibliographic coupling demonstrated more significant advantages compared with the commonly used approach of co-citation, as it produced a more accurate clustering result. Thus, we employ bibliographic coupling to classify the research field into a set of intellectual communities where the documents in each group are linked strongly. With the assistance of the Gephi program, we implement the community detection algorithm by Blondel et al. (2008) to sort out the intellectual communities in the IRC research field.

In summary, the co-citation network analysis is used for investigating the intellectual base of IRC studies, the main path analysis is applied to analyzing the main research trajectories in IRC studies, and the bibliographic coupling analysis is introduced to explore the intellectual communities in IRC research domains. We simultaneously apply these three kinds of approaches in our study because they can complement each other for a systematic overview of IRC literature. In fact, the co-citation network analysis is used for identifying the core "nodes" in the intellectual base from both longitudinal and transverse perspectives, and the main path analysis for the significant "links" in the research development trend from a longitudinal perspective, whereas the bibliographic coupling analysis is employed to find the main "clusters" in the research domain from a transverse perspective. So, the combination of these three complementary methods endows us with diverse perspectives in exploring the IRC knowledge domain.

2.2 Data Retrieval

The essential in citation-based analysis lies in the quality of data, which involves the process of selecting an appropriate data source as well as bibliographic metadata cleaning (Welpe et al., 2015). In this study, we adopt an important database in the Web of Science (WOS), namely, Social Sciences Citation Index (SSCI), as the data source. It is generally known that WOS is widely considered as the most comprehensive database for scholarly work as it indexes thousands of journals including some of the most prominent ones (Dahlander and Gann, 2010). Besides, WOS is deemed to be an appropriate database for overview analysis as it contains abundant citation data of documents. In this study, the data are retrieved from SSCI databases because the topic of IRC belongs to social science.

The definition of querying strategy of literature records is especially crucial for extracting a suitable dataset from vast amounts of database (Lu and Liu, 2014). Based on the querying approach suggested by experts in the IRC research field, we composed a ‘‘pilot query’’ consisting of a set of terms that are obtained from a preliminary review of the literature, and we used this query to look for data from the SSCI database. Then we used text mining analysis to extract key attributes and filter

the results to compose a list of candidate terms. Finally, the experts were consulted to screen and modify these candidate terms. The above processes were repeated several times until a convergent result was obtained. The final terms for the query were re-confirmed by the experts. Appendix A presents the details of our search strategies for IRC publications. We follow Ronda-Pupo and Katz (2017) to retrieve the documents by considering all peer-reviewed types, including Article, Note, Proceedings Papers and Review[6]. The time span of data was set to span from the year 1957 to 2015.

Figure 1 depicts the distribution of publication records of IRC research over entire period. We found that the IRC studies exhibited an "exponential growth" model. The publications appeared as early as the late 1950s, and the numbers have grown dramatically over the last decade. Based on the number of publications produced yearly, we can divide the entire period (1957-2015) into three development phases, namely, the emergence phase (1957-1991) with fewer than 20 publications in each year, the fermentation phase (1992-2005) with fewer than 40 publications in each year, and the "take off" phase (2006-2015) when the amount of publications exceeds 40 and exhibits a dramatically increasing trend. As shown in Figure 1, during the emergence phase (1957-1991), the publications were few and far between, indicating that IRC related topics had not captured much attention from scholars during the earlier period. It was not until 2006 that the research field entered into the "take off" phase. During this phase, IRC research grew tremendously and this trend continued, indicating that this research domain has sparked the interest of social scientists in recent years (Wagner, 2009). Moreover, a dramatic decrease in the barriers to entering this research area by social scientists is also an important factor causing a sharp increase in IRC studies. Due to the advancements of high powered computers and the availability of big databases such as Scopus and Web of Science publication database, as well as the development of free analytical tools like Pajek, CiteSpace, Gephi and R during this period, the social scientists have more chances to get involved in IRC studies even though they have limited programming skills. In other words, it is not just interest in IRC that is the growth driver - it is cheap and easy access to technology, tools and data that makes citation IRC studies accessible to many interested parties in the social sciences. As illustrated by Figure 1, in the year 2015, the largest number of publications (i.e., 160 in total) that devoted to this topic appeared, accounting for 10.73% of total documents in the IRC research domain, followed by the year 2014 with 152 publications (10.20%).

[6] The authors thank an anonymous reviewer for giving a valuable suggestion on our search strategies.

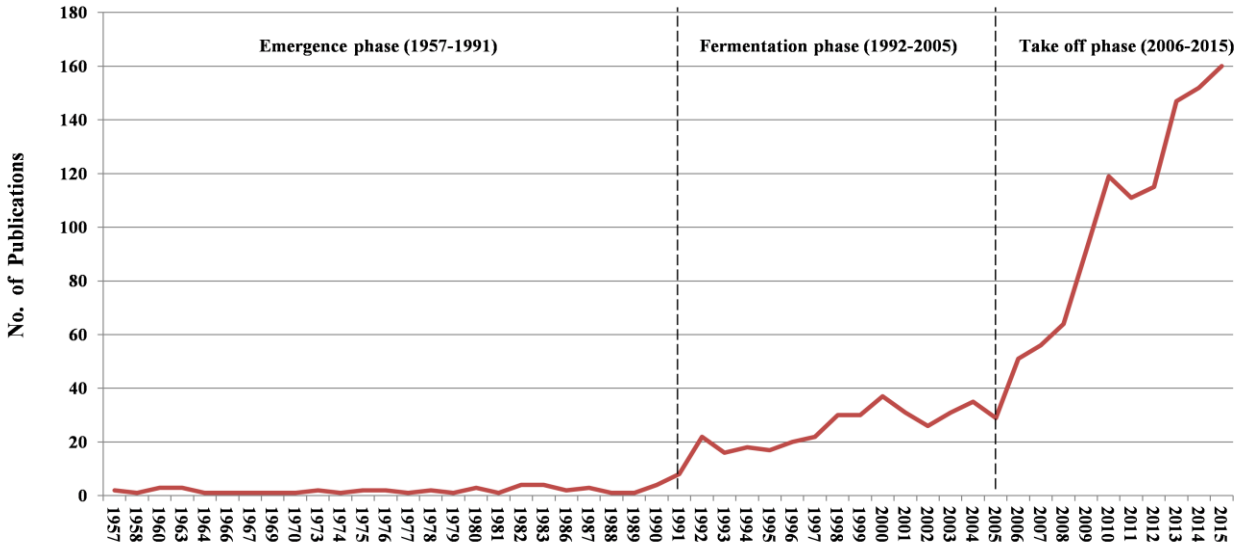

Fig. 1. Distribution of publications by year

3. Intellectual base of IRC research

As Persson (1994) noted, the citing publications form a research front, whereas the cited publications (i.e. reference) constitute an intellectual base. To explore the intellectual base of the IRC research, we construct a co-citation network of the references in order to detect the key publications which are highly cited by the documents from this research field. In this manner, the evolution footprints of the intellectual base of IRC research can be detected and monitored (Chen, 2003).

We implement the co-citation network analysis by running CiteSpace software. The number of top-cited references selected in constructing the co-citation network is an arbitrary number that needs to be selected with some care. On one hand, a small number will enable the complex co-citation network to be too simplistic. This leads to running the risk of neglecting some influential references. On the other hand, a very large number may add less influential references into the co-citation network, which blur the prominent structure of the intellectual bases of IRC studies, which defeats the purpose of applying the co-citation network analysis. CiteSpace allows us to examine different levels of details by selecting the number of top-cited references. We start the exploration by generating co-citation networks from the top 20, 30, 40 and 50 references and find that the top 30 references exhibit a relatively clear co-citation network. As the number increases, the co-citation network gradually becomes more complicated. We therefore determine to analyze the intellectual bases based on the top 30 references in each year with the assistance of CiteSpace software that was set to pathfinder network scaling. This contributes to the generation of Figure 2.

Figure 2 displays the reference co-citation network over the entire period 1957-2015. Influential

works can be recognized in the visualization maps because of prominent features they exhibit (Feng et al., 2015). Katz and Martin (1997) is the most highly cited publication in the intellectual base of IRC studies over the last almost 60 years. This work influences the IRC research domain by presenting an analytical framework for exploring research collaboration systemically. The second most important article in the intellectual base is Luukkonen et al. (1992), which explored the determinant of country-to-country differences in international scientific collaboration and found that some factors including language, geopolitical and historical factors can influence the scientific collaboration across countries. The third prominent article is Glänzel (2001), which explored the national characteristics of international scientific collaboration. The other most cited publications presented in Figure 2 show that Beaver and Rosen (1979) and Frame and Carpenter (1979) are the earliest publications that mainly employed the bibliometric method to characterize the research collaboration across countries.

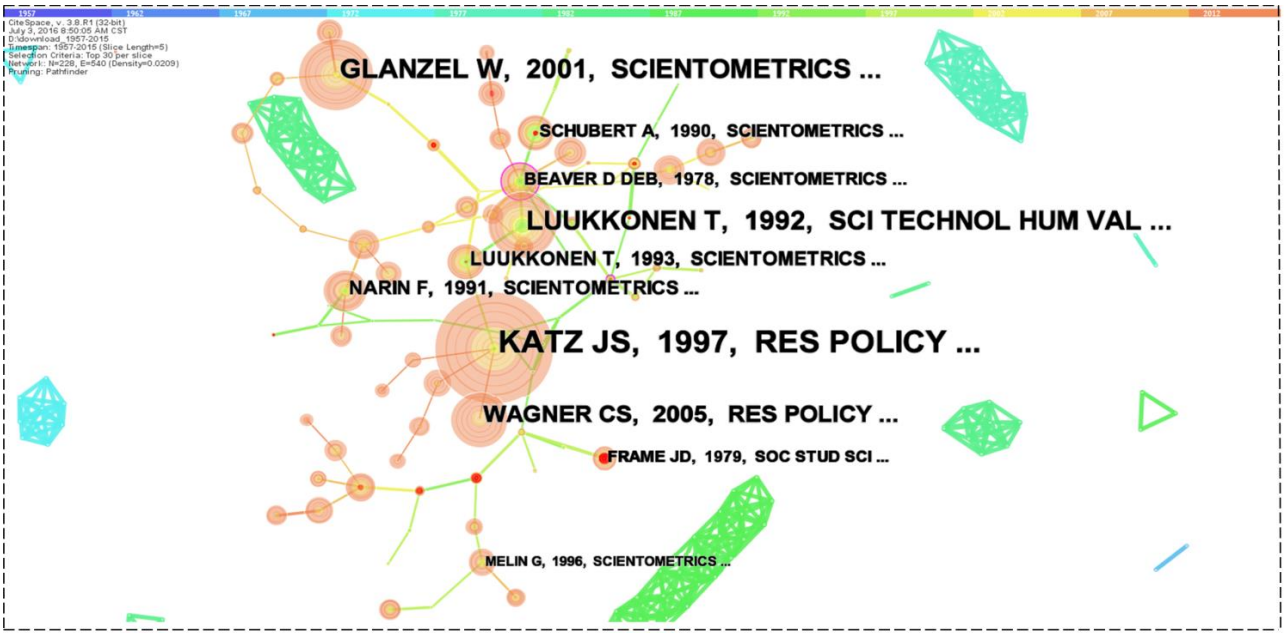

Fig. 2. Map of references in the IRC research domain.

Note: The top 30 references in each year were selected for constructing the co-citation network with the assistance of CiteSpace III software that was set to pathfinder network scaling.

In order to provide a temporal overview of the dynamic evolution of intellectual bases of IRC studies, we followed previous studies (Garfield, 2009; Garfield et al., 2003; Yu and Shi, 2015) and adopted two citation indexes, namely, local citation score (LCS) and global citation score (GCS), to identify the most-cited core references in the intellectual bases. LCS refers to the cited times by the current data set which consists of the documents retrieved from a particular research domain, while GCS indicates the total cited times by documents indexed in the whole database such as Scopus and Web of Science (Garfield, 2009; Garfield et al., 2003, 2006; Yu and Shi, 2015). Therefore, if a

publication's LCS is very high, it means that this publication acts as an important intellectual base of the research domain that is investigated due to its high frequency of being cited by documents from this research domain (Yu and Shi, 2015). By comparison, if a publication's GCS is high, it indicates that this publication attracts scientists' worldwide attention. It is possible that scholars in those research domains which are not related to your research discipline would cite this publication (Yu and Shi, 2015). Hence, compared with the GCS, the LCS is a more appropriate indicator that has been widely adopted to identify the core references in intellectual bases. Even so, the GCS value should be considered because it can reflect how much impact this work is having on research outside the boundaries of the particular domain. In this study, we identify the influential reference of IRC studies mainly according its LCS value, while its GCS value is also considered. The LCS and GCS values can be calculated with the assistance of HistCite[7] software and the Web of Science, respectively.

Table 1 presents the five most cited references constructing the intellectual base of IRC studies during three successive time periods starting in 1957. These core publications are identified and listed according to their LCS value. In the emergence phase (1957-1991), Frame and Carpenter (1979) has the highest LCS value during this phase, followed by Beaver and Rosen (1978, 1979). This indicates these early studies have attracted the attention of scholars from IRC research domain during early phase. In the fermentation phase (1992-2005), we clearly identify the five core references with highest LCS value, which include Frame and Carpenter (1979), Schubert and Braun (1990), Luukkonen et al. (1992), Luukkonen et al. (1993) and Beaver and Rosen (1978). These studies were the source of inspiration in this research field during this phase. The older work, Frame and Carpenter (1979), continued to be highly appreciated in this phase. In general, all these studies were based on exploration of internationally co-authored data, indicating that the co-authorship had been regarded as a reliable indicator for measuring IRC during this phase. In the "take off" phase (2006-2015), Katz and Martin (1997) was the most prominent publication in this phase, followed by Glänzel (2001), and Wagner and Leydesdorff (2005). It should be noted that Katz and Martin (1997) is the most-cited core reference of IRC studies in the entire phase (1957–2015). In response to the situation that international co-authorship was widely adopted to simply equate with IRC in many IRC studies, Katz and Martin (1997) is one of the early publications querying the validity of the bibliometric approach in IRC measurement. Even so, these top cited references in each phase continued to employ the bibliometric approach to investigate the IRC patterns.

[7] HistCite is software for analyzing and visualizing the direct citation linkages between publications indexed in Web of Science. Since HistCite can create a mini-citation index of the total references that are cited by the gathered documents used in the study, it would identify the documents ("outer references") whose titles do not contain the queried terms adopted by the original search for datasets. If these "outer references" have been cited by the datasets, HistCite can identify and add these related publications that originally were omitted from the datasets into the original "inner" collections (Garfield et al., 2006).

Table 1. Most cited references that constituted the intellectual base over three phases.

Rank	five top cited publications (references) in each phase	Local citation score (LCS) [a]	Global citation score (GCS) [b]
The emergence phase (1957-1991)			
1	Frame, J.D., Carpenter, M.P. (1979). International research collaboration. Social Studies of Science, 9: 481-497.	5	17
2	Beaver, D., Rosen, R. (1978). Studies in scientific collaboration: Part I. The professional origins of scientific co-authorship. Scientometrics 1(1), 65-84.	4	20
3	Beaver, D.D., Rosen, R. (1979). Studies in scientific collaboration: Part II. Scientific co-authorship, research productivity and visibility in the French scientific elite. Scientometrics 1(2), 133-149.	3	16
4	Price, D.d.S., 1963. Big science, little science. Columbia University, New York, 119-119.	2	12
5	Hansen, N. (1983). International-cooperation in border regions - an overview and research agenda. International Regional Science Review 8(3), 255-270.	2	10
The fermentation phase (1992-2005)			
1	Luukkonen, T; Persson, O; Sivertsen, G (1992). Understanding patterns of international scientific collaboration. Science Technology & Human Values, 17(1): 101-126.	32	79
2	Schubert A, Braun T (1990). International collaboration in the sciences, 1981-1985, Scientometrics, 19 (1-2): 3-10	28	57
3	Frame, J.D., Carpenter, M.P. (1979). International research collaboration. Social Studies of Science, 9: 481-497.	24	50
4	Luukkonen T, Tijssen RJW, Persson O, Sivertsen G (1993). The measurement of international scientific collaboration. Scientometrics, 28 (1): 15-36.	23	42
5	Beaver, D., Rosen, R. (1978). Studies in scientific collaboration: Part I. The professional origins of scientific co-authorship. Scientometrics 1(1), 65-84	22	68
The “take off” phase (2006-2015)			
1	Katz, JS, Martin, BR (1997). What is research collaboration? Research Policy, 26(1):1-18.	121	503
2	Glanzel, W (2001). National characteristics in international scientific co-authorship relations. Scientometrics, 51(1):69-115.	81	197
3	Wagner CS, Leydesdorff L (2005). Network structure, self-organization, and the growth of international collaboration in science. Research Policy, 34 (10): 1608-1618.	67	233
4	Luukkonen, T, Persson, O, Sivertsen, G (1992). Understanding patterns of international scientific collaboration. Science Technology & Human Values, 17(1): 101-126.	59	122
5	Narin, F, Stevens, K, Whitlow, ES (1991). Scientific cooperation in Europe and the citation of multinationally authored papers. Scientometrics, 21(3): 313-323.	46	123

The entire phase (1957–2015)			
1	Katz, JS, Martin, BR (1997). What is research collaboration? Research Policy, 26(1):1-18.	137	587
2	Luukkonen, T; Persson, O; Sivertsen, G (1992). Understanding patterns of international scientific collaboration. Science Technology & Human Values, 17(1): 101-126.	91	220
3	Glanzel, W (2001). National characteristics in international scientific co-authorship relations. Scientometrics, 51(1):69-115.	90	255
4	Wagner CS, Leydesdorff L (2005). Network structure, self-organization, and the growth of international collaboration in science. Research Policy, 34 (10): 1608-1618.	67	265
5	Narin, F, Stevens, K, Whitlow, ES (1991). Scientific cooperation in Europe and the citation of multinationally authored papers. Scientometrics, 21(3): 313-323.	64	199

Note: [a] This index refers to the number of cited times by the IRC studies during corresponding stages.

[b] This index refers to the total cited times by publications in the Web of Science during corresponding stages.

As shown in Table 1, compared with LCS values, the GCS values of these core references are quite high. This is not surprising because GCS values include citations not only from IRC studies but also from other research domains. For example, the GCS value of Katz and Martin (1997) is 587 during entire phase (1957-2015), while its LCS value is only 137. This suggests that Katz and Martin (1997) has multidisciplinary impact outside the boundaries of IRC research domain. How these documents with high GCS values influence the knowledge domain outside of the IRC domain. This issue is beyond the scope of our study but indicates the directions for future research.

Furthermore, in order to track the evolution path of the intellectual base of IRC research over the entire period, we run CiteSpace by setting slice length to 5, and the top 30 references in each slice were selected for constructing time-zone visualization. This contributes to the generation of Figure 3, which shows the evolution path of the intellectual base during the period 1957 to 2015 from a time-zone perspective. Clearly, the earlier important cited documents appeared during the 1960s, namely, Price (1963) and Price and Beaver (1966). They obtained multi-period citations and presented stable intellectual bases for the long-term development in the IRC research field. This is not surprising because adopting co-authorship to measure research collaboration has become an interesting theme since the 1960s (e.g., Price and Beaver, 1966; Price 1963). Price's work "Little Science, Big Science", constituting the intellectual bases of IRC studies, is one of the most cited publications in the early time period. This also reflects that the IRC is mainly under the influences of earlier statistically and quantitatively oriented scholars. Moreover, some core studies appeared in the late 1970s, for example, Frame and Carpenter (1979) and Beaver and Rosen (1978, 1979). These works are the early studies applying co-authorship data, a bibliometric method introduced by Price (1963) and Price and Beaver (1966), to characterize research collaboration across countries.

Subsequently, many key works, such as Wagner and Leydesdorff (2005), Schubert and Braun (1990), Katz and Martin (1997), were closely linked in the 1990s and early 21st century.

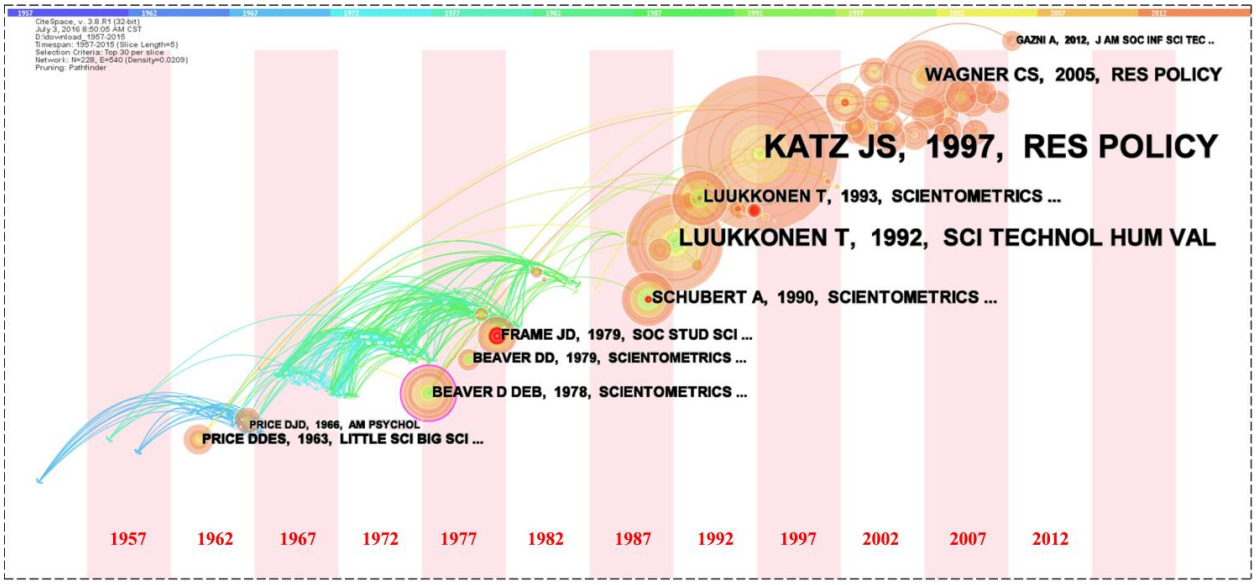

Fig. 3. Map of the references in the IRC research domain from a timeline perspective.

Note: Slice length was set to 5 and the top 30 references in each slice were selected for constructing time-zone visualization with the assistance of CiteSpace III software.

Based on a temporal overview of the dynamic evolution of intellectual bases of IRC studies over the entire period 1957-2015, we find that it was not until the late 1970s that international co-authorship analysis was used as the mainstream technique for measuring IRC. Since the 1990s, the introduction of the co-authorship data to quantify IRC became widespread. This constitutes the intellectual evolution path of the IRC research from a time-zone perspective.

4. Main research trajectories in the IRC research domain

Tracing the main research trajectories in a small research domain may be an easy task as scholars do not have to devote great efforts to review a small amount of literature. However, when the research domain grows even larger, the difficulty of tracing the main research trajectories increases significantly. Hummon and Dereian (1989) introduced a quantitative approach, namely, main path analysis, to simplify a large and complicated research domain to one or several main trajectories (paths) consisting of some key nodes and their links, as shown in Figures 4-7. These figures are drawn by using Pajek software (Batagelj and Mrvar, 1998), which is a software program for the analysis and visualization of networks.

As mentioned earlier, the main path analysis is executed based on the key-route algorithm, which can be automatically implemented with the assistance of Pajek software, but the number of top

citation links selected in drawing key-route main paths is an arbitrary number that needs to be selected with some care. On one hand, a small number will reduce the key-routes main paths to too few paths, such that no divergent-convergent pattern can be observed. On the other hand, a very large number may add paths that include less significant citation links, which blur the governing structure of the knowledge diffusion paths. In the extreme, the key-route main paths will become the original citation networks, which defeats the purpose of applying the main path analysis. The key-route approach allows us to examine different levels of details by selecting the number of important links. We start the exploration by generating key-route paths from the top 10, 20, 30, and 40 links with the highest SPC values and find that top citation links between 20 and 30 exhibit relatively clear divergent-convergent patterns. As the number increases, the pattern is gradually blurred by less significant citation links. We therefore determine to analyze the key-route main paths based on the top 30 links, which contributes to generating distinct main research trajectories consisting of crucial nodes and arrows (as shown in Figures 4-7). In these figures, each node represents a document, and the arrows demonstrate the cited and citation relationships between the documents, indicating knowledge flow between them. The main trajectory represents the largest part of the knowledge flows within the research domain (Bhupatiraju et al., 2012). After investigating these documents in the main paths, we can efficiently gain an impression of the main research trajectories in a particular scientific discipline.

4.1. The emergence phase (1957-1991)

During the early phase, the main research trajectories consisted of the documents that investigated the patterns of IRC, based on international co-authorship data. Figure 4 illustrates the main research trajectory during 1957–1991, and Table 2 presents the crucial nodes (publications) in the research main path. We found that the main path of this period was very simple, as it consisted of only five nodes (for details please refer to Table 2), among which the first two nodes were the ‘sources’ (which refers to the pioneering works which were widely cited by subsequent publications, but which cited no other prior studies), and the last two nodes were the “sinks” (which refers to the latest research that cited prior studies, but which has not yet been cited). One of the ‘sources’ of the main path was Beaver and Rosen (1978), and the other one was Beaver and Rosen (1979). After investigating these two publications, we found that Beaver and Rosen (1978) is a pioneering work which presented IRC theory for comprehensively interpreting the international collaboration across countries in the scientific research field. Beaver and Rosen (1979) further examined and tested the theory by Beaver and Rosen (1978). In these two studies, the authors attempted to construct a systematic framework within which IRC incidence, patterns, functions, and value were investigated and they concluded that research collaboration appeared in response to an increasingly professional

trend in the scientific research field.

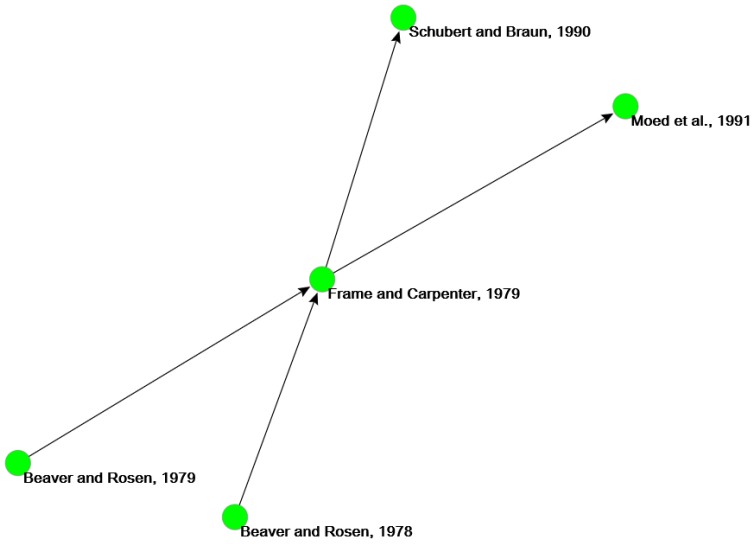

Fig. 4. The research main path during 1957-1991

Note: With assistance of Pajek software, the research trajectory is drawn based on the algorithm of key-route main path.

Table 2. Crucial nodes (publications) in the research main path during 1957-1991.

Name of author	Title	Year
Beaver and Rosen	Studies in scientific collaboration: Part I. The professional origins of scientific co-authorship	1978
Beaver and Rosen	Studies in scientific collaboration: Part II. Scientific co-authorship, research productivity and visibility in the French scientific elite	1789
Frame and Carpenter	International research collaboration	1979
Schubert and Braun	International collaboration in the sciences 1981–1985	1990
Narin et al.	Scientific co-operation in Europe and the citation of multinationally authored papers	1991

As shown in Figure 4, both of the studies by Beaver and Rosen (i.e., Beaver and Rosen, 1978, 1979) later merged onto a subsequent node in the main path: Frame and Carpenter (1979), which is also another early study that introduced bibliometric analyses of co-authorships to examine IRC patterns in nine scientific research fields. Frame and Carpenter (1979) was later cited by two "sinks" in the main path: Schubert and Braun (1990) and Narin et al. (1991). In particular, Schubert and Braun (1990) followed previous studies and employed international co-authorships as an indicator to measure research collaborations across 167 countries. In addition, Narin et al. (1991) investigated the patterns of transnational scientific collaboration and found that IRC across the European countries had been enhanced. Besides, this study also confirmed that those highly cited works produced by

European countries were internationally co-authored papers.

Overall, two ‘sources’ of the main path, Beaver and Rosen (1978, 1979), established a theoretical base for the IRC research field. Frame and Carpenter (1979) followed Beaver and Rosen (1978, 1979) and used the bibliometric co-author method for investigating IRC, and this methodology was also adopted by following studies such as Schubert and Braun (1990) and Narin et al. (1991).

4.2. The fermentation phase (1992-2005)

During this phase, the main research trajectories consisted of the documents that not only investigated the IRC patterns but also explored the motivations of IRC as well as its effects. The research main path during 1992-2005 is shown in Figure 5, and Table 3 presents the crucial nodes (publications) in the research main path. We found that the main research path was composed of ten nodes (for detail please refer to Table 3), suggesting it was significantly longer compared with that in earlier period. We found that the ‘source’ of the main path was Luukkonen et al. (1992), and then two sub-paths appeared after the second node Luukkonen et al. (1993). The one sub-path on the right of the figure consisted of Glänzel and de Lange (1997), Glänzel et al. (1999) and Glänzel (2001). The other sub-path on the left of the figure was composed of Katz and Martin (1997) and Zitt et al. (2000). These two sub-paths later converged on Glänzel and de Lange (2002), and then no divergence was observed. Thereafter, a merged main path consisting of Glänzel and de Lange (2002), Wagner (2005), Wagner and Leydesdorff (2005), appeared.

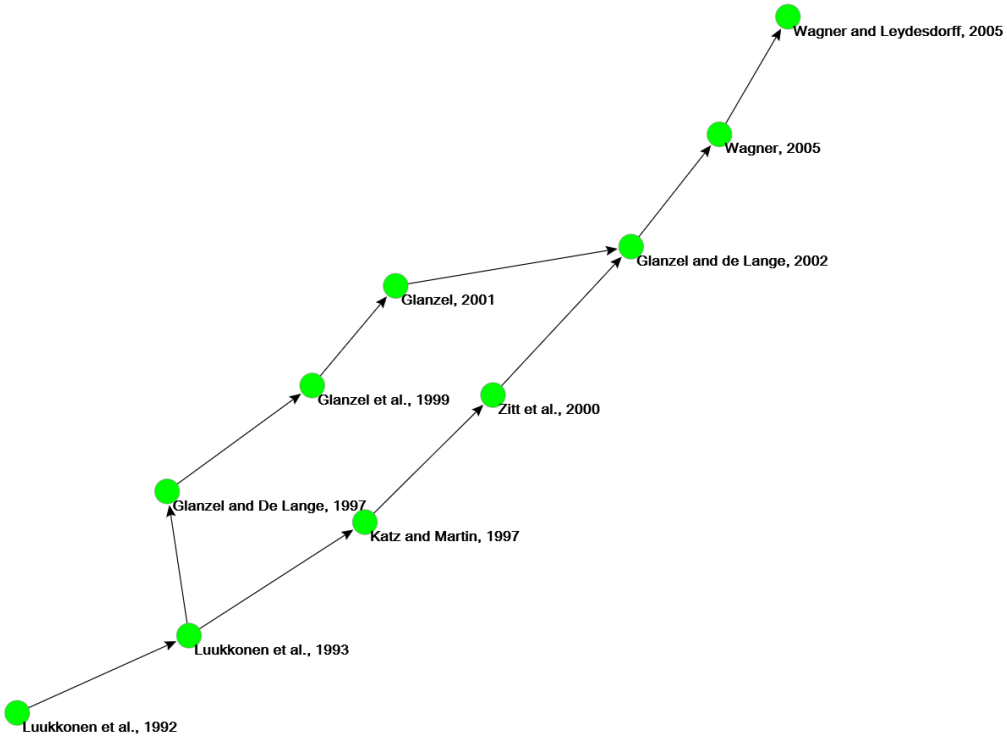

Fig. 5. The research main paths during 1992-2005

Note: The research trajectory is drawn based on the algorithm of key-route main path using Pajek software.

Table 3. Crucial nodes (publications) in the research main path during 1992-2005.

Name of author	Title	Year
Luukkonen et al.	Understanding patterns of international scientific collaboration	1992
Luukkonen et al.	The measurement of international scientific collaboration	1993
Katz and Martin	What is research collaboration?	1997
Glänzel and De Lange	Modelling and measuring multilateral co-authorship in international scientific collaboration. Part II. A comparative study on the extent and change of international scientific collaboration links	1997
Glänzel et al.	A bibliometric analysis of international scientific cooperation of the European Union (1985–1995)	1999
Zitt et al.	Shadows of the past in international cooperation: Collaboration profiles of the top five producers of science	2000
Glänzel	National characteristics in international scientific co-authorship relations	2001
Glänzel and de Lange	A distributional approach to multinationality measures of international scientific collaboration	2002
Wagner	Six case studies of international collaboration in science	2005
Wagner and Leydesdorff	Network structure, self-organization, and the growth of international collaboration in science	2005

Since the 1990s, the co-authorship data have been regarded to be a reliable indicator for quantifying research collaboration (Franceschet and Costantini, 2010). A host of bibliometric studies based on the analysis of the co-authored relationship appeared in the IRC research domain (Lewison and Cunningham, 1991; Narin et al., 1991; Schubert and Braun, 1990; Moed et al., 1991), which aimed at measuring IRC patterns and exploring their determinants and impacts. For example, Luukkonen et al. (1992) investigated how the potential determinants, such as geopolitical, cognitive, economic, historical and social factors, influence the patterns and rates of international scientific collaborations of different countries. The next study in the main path, Luukkonen et al. (1993), attempted to clarify the methodology that was being used or could be used for measuring the IRC, and concluded that the relative and absolute measures should be employed simultaneously for analyzing the research collaboration links between countries. The following node on the left branch, Glänzel and de Lange (1997), presented an important model by which the extent of multilateral IRC relationships across the countries could be measured and analyzed effectively. The following node on the right branch, namely, Katz and Martin (1997), not only defined the connotation of "research collaboration" but also presented discussions on the costs and benefits of research collaboration. Besides, this study queried the validity and applicable of using the co-authorship to characterize

research collaboration. This methodology has been widely adopted by IRC studies since the 1990s (Narin et al., 1991; Luukkonen et al., 1993). The next publication following Glänzel and de Lange (1997) on the left branch, namely, Glänzel et al. (1999), was an empirical study on scientific collaboration of EU countries with other developed regions. Similar to most bibliometric studies on research collaboration links among various countries, this study was also concerned with the patterns of IRC as well as its impacts on the research performance of different countries. The following node, namely, Glänzel (2001), afforded a deep insight into the international co-authorship patterns of 50 selected countries with one another. The next publication, Zitt et al. (2000), aimed at a characterization of international collaborative behaviors of five important countries (i.e., Japan, United Kingdom, Germany, United States and France). The converging node, Glänzel and de Lange (2002), developed a simple but efficient model to inspect IRC patterns in some subfields of science. Wagner (2005) sought to explore the intrinsic properties of IRC as well as some driving factors that may influence IRC patterns at the disciplinary level. This study suggested that the motivations including searching for complementary resources, sharing facilities, likely promoted international scientific collaboration. Wagner and Leydesdorff (2005) attempted to interpret the fast increments of international scientific collaboration from a network perspective.

By investigating core studies in the main path during this period, we found that the international co-authorships in publications were widely accepted as proxy for IRC since the 1990s (e.g., Glänzel and de Lange, 2002; Glänzel et al., 1999; Luukkonen et al., 1992) even though the validity of this technique has been queried by some influential studies (e.g., Katz and Martin, 1997). Moreover, some scholars not only developed some indicators to characterize the research collaboration among the countries, but also explored what may affect the IRC patterns (e.g., Wagner, 2005; Wagner and Leydesdorff, 2005), as well as any benefit from IRC behavior (Glänzel et al., 1999).

4.3. The "take off" phase (2006-2015)

During this phase, the main research trajectories consisted of the documents that largely focused on IRC patterns and its effects. Figure 6 demonstrates the research main path during 2006-2015, and Table 4 presents the crucial nodes in detail. We can find that the research main path had two 'sources', namely, Kim (2006) and Anuradha and Urs (2007), which merged to Sooryamoorthy (2009). After that, the research main path consisting of two nodes (i.e., Hayati and Didegah, 2010; Gazni et al., 2012) appeared, and then it branched into two sub-paths. The sub-path on the left of the figure consisted of four documents, namely, Niu and Qiu (2014), Vakilian et al. (2015), Tan et al. (2015) and Li and Li (2015), among which the last three documents were the "sinks" of the main path during this period. The other sub-path on the right of the figure was composed of three

documents, namely, Bote et al. (2013), Zhou and Tian (2014) and Zhou and Lv (2015).

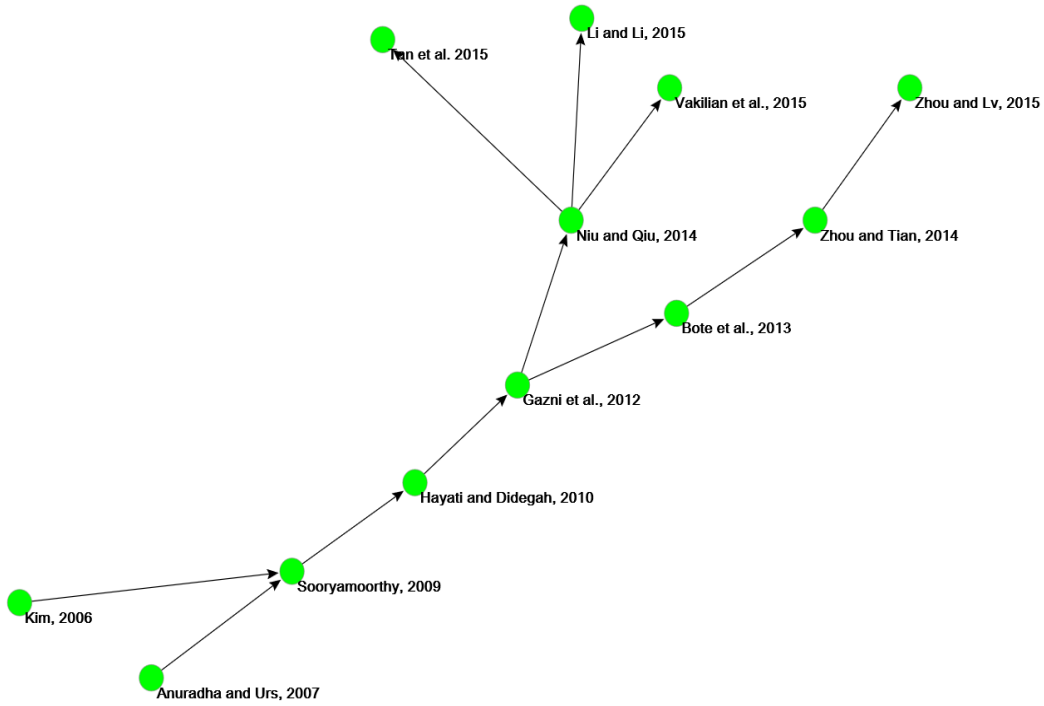

Fig. 6. The research main path during 2006-2015

Note: The research trajectory is drawn based on the algorithm of key-route main path using Pajek software,

Table 4. Crucial nodes (publications) in the research main path during 2006-2015.

Name of author	Title	Year
Kim	Measuring international research collaboration of peripheral countries: Taking the context into consideration	2006
Anuradha and Urs	Bibliometric indicators of Indian research collaboration patterns: A correspondence analysis	2007
Sooryamoorthy	Do types of collaboration change citation? Collaboration and citation patterns of South African science publications	2009
Hayati and Didegah	International scientific collaboration among Iranian researchers during 1998-2007	2010
Gazni et al.	Mapping world scientific collaboration: Authors, institutions, and countries	2012
Bote et al.	Quantifying the benefits of international scientific collaboration	2013
Niu and Qiu	Network structure, distribution and the growth of Chinese international research collaboration	2014
Zhou and Tian	Funded collaboration research in mathematics in China	2014
Zhou and Lv	Academic publishing and collaboration between China and Germany in physics	2015
Vakilian et al.	A bibliometric analysis of lab-on-a-chip research from 2001 to 2013	2015
Tan et al.	Impact analysis of domestic and international research collaborations: a Malaysian case study	2015
Li and Li	Patterns and evolution of co-authorship in China's humanities and social sciences	2015

As shown in Figure 6, Anuradha and Urs (2007) and Kim (2006) were the 'sources' in the research main path during this phase. Both of these two "sources" described the case studies on the scientific collaboration of a particular country with other countries. Specifically, Kim (2006) investigated international science collaboration of Korea with other countries, while Anuradha and Urs (2007) analyzed IRC patterns of India with other countries in different disciplines by using bibliometric indicators. These two studies contributed to a better understanding of IRC properties of scientifically "peripheral" countries such as Korea and India. Later, these two nodes converged on Sooryamoorthy (2009). This study found that IRC exerted a positive influence on research performance. However, the next node in the research main path, namely, Hayati and Didegah (2010), explored the situation and rate of research collaboration of Iran with international counterparts and found that international collaboration did not always result in good research performance – at least in the case of Iran. This suggests that the effects of IRC were still inconclusive. The following node Gazni et al. (2012) provided a global description of IRC behaviors in the context of multiple domains and all countries, which gave an important insight into the different IRC behaviors in different research domains or countries.

There are two streams of research on the effect of IRC: most previous studies confirmed that scientific productions and impacts can be enhanced by IRC (e.g., Gomez et al., 1999; Schmoch and Schubert, 2007; Lancho Barrantes et al., 2012), yet some scholars argued that this was not always true (e.g., Hayati and Didegah, 2010; Harirchi et al., 2007). This indicated that not all countries can derive the same benefit from international collaboration. Why? A core study on the sub-path, namely, Bote et al. (2013), tried to answer this question by examining which countries obtained the greatest benefit from international collaboration and which countries provided the greatest benefit to their collaborating countries. The result showed that high-impact countries such as the USA did not gain any great benefit from international collaboration for enhancing their scientific impact, whereas low-impact countries significantly benefited from international collaboration with high-impact countries. The following node on the same sub-main path, namely, Zhou and Tian (2014), tried to explore the impacts of all kinds of collaborations (including international collaboration) on academic productivity and found that international collaboration performed better in raising productivity compared with other kinds of collaborations. The last node on the main path, i.e., Zhou and Lv (2015), investigated the bilateral collaboration between Germany and China in the physics domain and found that both these countries got benefits from IRC. As a whole, the studies in this sub-main path mainly focused on the effect of international collaboration and found that this effect exhibited different results for different countries.

The other research sub-path starts with Niu and Qiu (2014), which not only applied a bibliometric approach and but also introduced a social network perspective to highlight IRC behavior between China and its partners. Following Niu and Qiu (2014) there are three sink nodes in this sub-path, namely, Tan et al. (2015), Li and Li (2015) and Vakilian et al. (2015). More specifically, Tan et al. (2015) implemented the impact assessment of domestic and international research and showed that Malaysia benefited from scientific collaboration. Li and Li (2015) explored the dynamic patterns of scientific collaboration between China and other countries in the research field of humanities and social sciences, hence providing a historical perspective of the structure and dynamics of China's IRC in this field. Vakilian et al. (2015) investigated IRC across the most important (top 20) countries in the lab-on-a-chip research domain from a network perspective. On the whole, these studies in this research sub-path mainly employed the network perspective to implement the research on international scientific collaboration in the context of a particular field or country from. Except for Vakilian et al. (2015), other studies focused on a particular country's IRC patterns, especially the developing countries among which China is the obvious one.

Based on the analysis of the core studies in the main path during this period, we found that the effect of IRC has become a hot topic (e.g., Bote et al., 2013; Schmoch and Schubert, 2007; Gomez et al., 1999; Lancho Barrantes et al., 2012; Tan et al., 2015). Besides, the patterns of a particular country's collaboration with other countries have increasingly drawn the interest of scholars during this period (e.g., Li and Li, 2015; Niu and Qiu, 2014; Tan et al., 2015). However, the studies that present a global description of IRC patterns across various fields and countries are still scant except Gazni et al. (2012).

4.4. The entire phase 1957–2015

During the entire phase, the main research trajectories consisted of documents that mainly adopted co-authorship as the proxy of IRC to examine research collaboration across different countries. Figure 7 and Table 5 summarize the research trajectory of IRC studies during the entire period. Specifically, Figure 7 presents the research main path in IRC studies from 1957 to 2015, and the crucial nodes (publications) in the research main path are shown in detail in Table 5. There are 32 important publications in the main path, which started with Beaver and Rosen (1978, 1979). Later they consolidated in Frame and Carpenter (1979) and then disseminated into two papers: Schubert and Braun (1990) and Luukkonen et al. (1992); and then the path passed through a series of nodes (publications) that focused on various IRC topics, and end with four papers, namely, Zhou and Lv (2015), Vakilian et al. (2015), Tan et al. (2015) and Li and Li (2015).

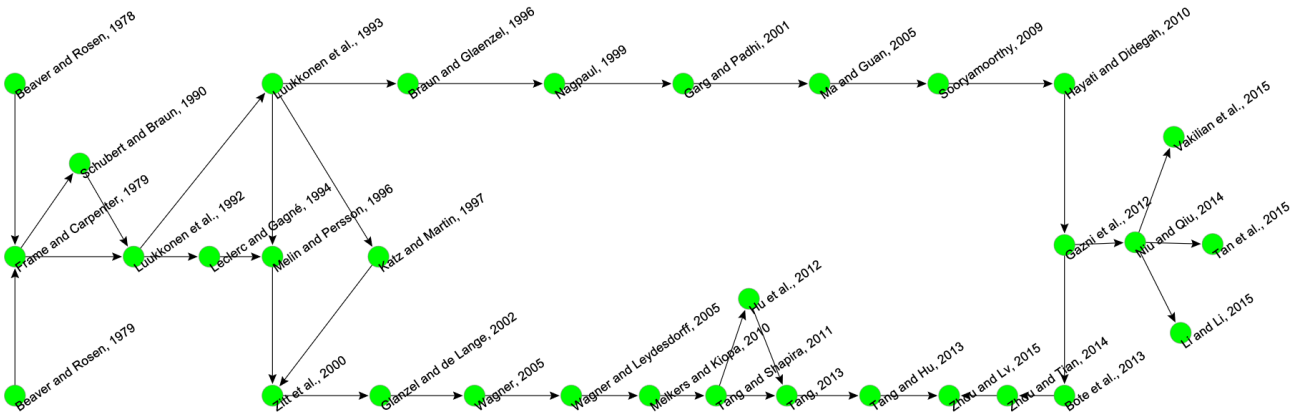

Fig. 7. The research main path during 1957-2015

Note: The research trajectory is drawn based on the algorithm of key-route main path using Pajek software.

Table 5. Crucial nodes (publications) in the research main path during 1957-2015.

Name of author	Title	Year
Beaver and Rosen	Studies in scientific collaboration: Part I. The professional origins of scientific co-authorship	1978
Beaver and Rosen	Studies in scientific collaboration: Part II. Scientific co-authorship, research productivity and visibility in the French scientific elite	1789
Frame and Carpenter	International research collaboration	1979
Schubert and Braun	International collaboration in the sciences 1981–1985	1990
Luukkonen et al.	Understanding patterns of international scientific collaboration.	1992
Luukkonen et al.	The measurement of international scientific collaboration	1993
Leclerc and Gagné	International scientific cooperation: The continentalization of science	1994
Melin and Persson	Studying research collaboration using co-authorships	1996
Braun and Glaenzel	International collaboration: Will it be keeping alive East European research?	1996
Katz and Martin	What is research collaboration?	1997
Nagpaul	Transnational linkages of Indian science: A structural analysis	1999
Zitt et al.	Shadows of the past in international cooperation: Collaboration profiles of the top five producers of science	2000
Garg and Padhi	A study of collaboration in laser science and technology	2001
Glänzel and de Lange	A distributional approach to multinationality measures of international scientific collaboration	2002
Ma and Guan	An exploratory study on collaboration profiles of Chinese publications in Molecular Biology	2005
Wagner and Leydesdorff	Network structure, self-organization, and the growth of international collaboration in science.	2005
Sooryamoorthy	Do types of collaboration change citation? Collaboration and citation patterns of South African science publications	2009
Hayati and Didegah	International scientific collaboration among Iranian researchers during 1998-2007	2010
Melkers and Kiopa	The social capital of global ties in science: The added value of international collaboration	2010

Tang and Shapira	China–US scientific collaboration in nanotechnology: Patterns and dynamics	2011
Gazni et al.	Mapping world scientific collaboration: Authors, institutions, and countries	2012
Hu et al.	Visualizing nanotechnology research in Canada: Evidence from publication activities, 1990–2009	2012
Tang	Does "birds of a feather flock together" matter—Evidence from a longitudinal study on US–China scientific collaboration	2013
Tang and Hu	Tracing the footprint of knowledge spillover: Evidence from US–China collaboration in nanotechnology	2013
Bote et al	Quantifying the benefits of international scientific collaboration	2013
Niu and Qiu	Network structure, distribution and the growth of Chinese international research collaboration	2014
Zhou and Tian	Funded collaboration research in mathematics in China	2014
Zhou and Lv	Academic publishing and collaboration between China and Germany in physic	2015
Vakilian et al.	A bibliometric analysis of lab-on-a-chip research from 2001 to 2013	2015
Tan et al.	Impact analysis of domestic and international research collaborations: a Malaysian case study	2015
Li and Li	Patterns and evolution of coauthorship in China's humanities and social sciences	2015

By identifying and reviewing the core studies in the main path during 1957-2015, as shown in Figure 7 and Table 5, we can track the main flow of ideas in IRC studies. Although some scholars implemented IRC studies at the end of the 1950s (e.g., Bleuler, 1958; Watt, 1957), these early studies had not entered into the research main paths. This may be because the methodologies of observation, interviews or questionnaire used by earlier studies were not adopted by subsequent publications that mainly relied on the bibliometric analysis of co-authored documents. In the late 1970s, Beaver and Rosen (1978, 1979) and Frame and Carpenter (1979) were the early studies entering the research main path in the IRC research domain.

During the 1990s, the IRC research became abundant. Some studies, such as Schubert and Braun (1990) and Nagpaul (1999), investigated the IRC patterns across countries. In addition, some studies paid particular attention to the factors that influenced IRC behavior (e.g., Luukkonen et al., 1992; Leclerc and Gagné, 1994; Braun and Glaenzel, 1996). In response to the increasing popularity of using co-authored publications to reflect the structure and change of research collaborative relationships, Katz and Martin (1997) and Melin and Persson (1996) queried the validity of adopting co-authored data alone as an indicator to characterize actual relationships of research collaboration across countries.

Since the 2000s, the IRC research entered the boom stage with an abundance of literature. The IRC patterns still attracted the attention of scholars during this period. For example, Garg and Padhi (2001) introduced some indexes to identify the collaboration patterns between different countries.

Gazni et al. (2012) sought to measure the research collaboration patterns within some fields and countries. With widespread appearance of IRC, some studies tested the impacts of international collaboration (e.g., Bote et al., 2013; Ma and Guan, 2005; Sooryamoorthy, 2009). Besides, the IRC patterns of a particular country with other countries have become an important topic arousing scholars' interest in recent years (Niu and Qiu, 2014; Li and Li, 2015; Tan et al., 2015).

5. Intellectual communities (categories) in IRC studies

Apart from investigating the research trajectory of IRC studies over the period between 1957 and 2015 from a longitudinal perspective, we also provide a holistic and comprehensive review on this research domain from a transverse perspective. For this purpose, we created a bibliographic coupling network of IRC documents by using a normalized similarity measurement based on the Cosine index (Salton and McGill, 1983). To demonstrate the clusters in the bibliographic coupling map, the threshold level used to select the number of the bibliographic coupling links in drawing intellectual communities is an arbitrary number that needs to be selected with some care. We start the exploration by generating the clusters in the bibliographic coupling map by setting the threshold level at 2, 3, 4 and 5 with the bibliographic coupling links, and find that the bibliographic coupling links with more than 4 exhibit relatively clear intellectual communities in the IRC research field. So, we selected the bibliographic coupling links with more than 4 to create a bibliographic coupling network of IRC documents, which is illustrated by Figure 8. Then the representative studies (presented by Table 6) in each intellectual category are detected and we read them carefully and summarize the research topics of different subdomains of IRC studies. As shown in Figure 8, the result from the cluster detection analysis is based on the color coding of network nodes depending on the category to which they belong. We discovered five distinct but interrelated clusters or modular structures consisting of closely connected publications in the IRC research domain.

After intensively studying the title, abstract and keywords of each publication in each cluster, we discern and label five clusters according to their main content. That is, (1) Driving factors of IRC; (2) IRC patterns; (3) IRC effects; (4) IRC networks; (5) IRC measurement. In this paper, we explore each of these clusters from a systematic review.

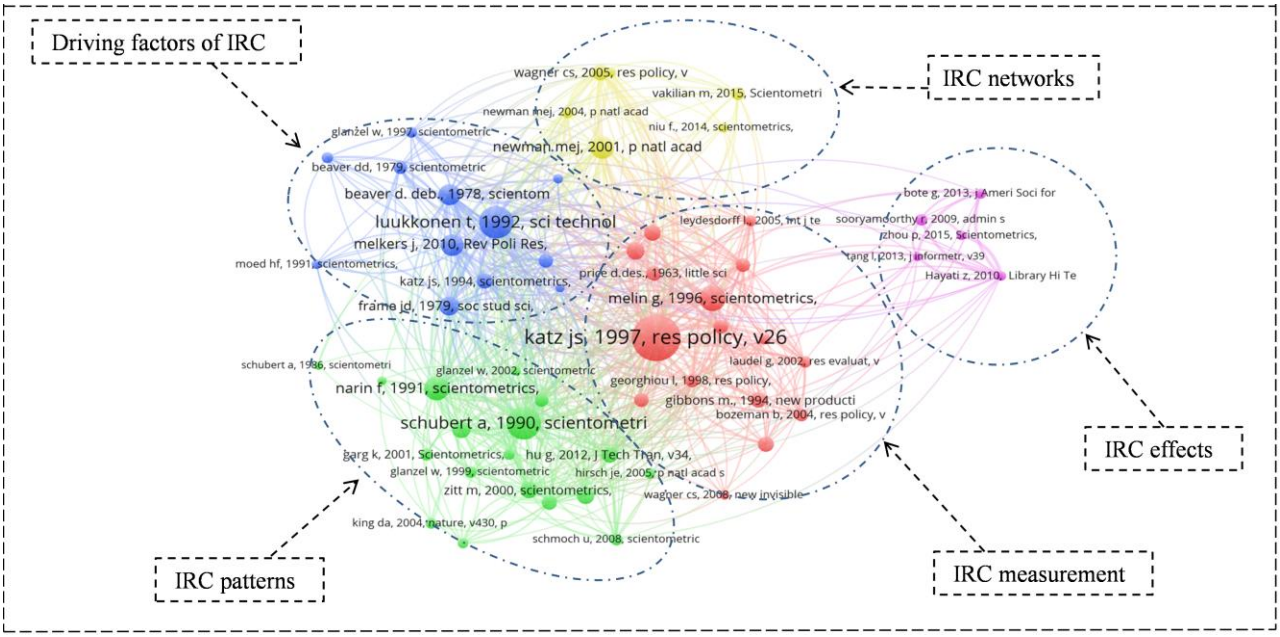

Fig. 8. Bibliographic coupling map of the IRC literature.

Note: The bibliographic coupling map is drawn with assistance of Gephi program. To vividly demonstrate the clusters in the bibliographic coupling map, the bibliographic coupling links with more than 4 were selected.

Table 6. Representative studies of intellectual communities (categories) in IRC studies

Categories name	Representative studies
Driving factors of IRC	Beaver and Rosen,1978, 1979; Frame and Carpenter, 1979; Luukkonen et al., 1992; Melin, 1999; Wagner, 2005; Melkers and Kiopa,2010; Zhao et al., 2013
IRC patterns	Schubert and Braun, 1990; Garg and Padhi, 2001; Glänzel and Winterhager, 1992; Nagpaul, 1999; Gazni et al., 2012; Tan et al., 2015; Vakilian et al., 2015
IRC effects	Narin et al., 1991; Ma and Guan, 2005; Schmoch and Schubert, 2007; Sooryamoorthy, 2009; Hayati and Didegah, 2010; Tang, 2013
IRC networks	Newman, 2001, 2004; Wagner and Leydesdorff, 2005; Niu and Qiu, 2014; Kumar and Jan, 2014; Vakilian et al., 2015
IRC measurement	Melin and Persson, 1996; Katz and Martin, 1997; Laudel, 2002

5.1. Driving factors of IRC

As shown in Figure 8 and Table 6, the first (blue) cluster is dominated by the studies on the factors contributing to IRC behavior. Since the late 1970s, the fundamental mechanisms regarding different determinants of IRC have been the subject of studies, among which Frame and Carpenter (1979) and Beaver and Rosen (1978, 1979) explored the factors affecting international scientific collaboration. Beaver and Rosen (1978, 1979) showed that the driving factors of IRC included

enhancing productivity and impact, professional orientation and so on. Frame and Carpenter (1979) proved that different disciplines, the size of national science and other extra-scientific factors exerted influence on the extent of IRC. Later, Luukkonen et al. (1992) investigated the potential determinants that influenced the propensity of countries to collaborate internationally. Melin (1999) examined the impact of country size on IRC by discerning the difference between American and European universities. Wagner (2005) explored the motivations affecting IRC patterns. Melkers and Kiopa (2010) examined what determines the development of international collaboration in science.

By and large, these studies proved that a set of factors, such as political (international and regional political interests), economic (inexpensive communication), cognitive (research capability), spatial (geographical location) and social (historical, cultural and linguistic proximities) ones, had an impact on IRC. In particular, although the great advancements of telecommunication technology have created new possibilities for countries located far away to form collaborative linkages with one another (Anuradha and Urs, 2007; Zhou and Tian, 2014), geographical proximity still has a significant influence on IRC collaboration, because the face-to-face contacts enable more complex and intense forms of interactions in which not only language is involved but also the entire behavioural complex (such as subtle communication, informal interaction), which cannot easily be achieved with the assistance of modern communication media (Hoekman et al., 2010). Empirically, after the Luukkonen et al (1993) study of international collaboration that suggested an effect of geographical proximity on research collaboration, it was confirmed and refined by a series of later studies (e.g., Katz, 1994; Davids and Frenken, 2018; Ponds et al., 2007), which suggested that geographical proximity still plays a role in IRC even in the modern telecommunications era.

Moreover, the governments take some initiative measures, such as setting up the inter-governmental S&T programs, to enhance IRC efforts. This is an important driving factor of IRC. It should be noted that previous studies have proposed that IRC is driven by one or a combination of several motivations: 1) accessing the scarce or unique resources such as data, information, research samples in other countries (Zhao et al., 2013); 2) seeking for the complementary capabilities including diverse ideas, skills and data analysis capabilities (Beaver and Rosen, 1979; Wagner and Leydesdorff, 2005); 3) sharing the high cost of large-scale equipment or long-term research (Wagner, 2005).

5.2. IRC patterns

The second (green) cluster shown in Figure 8 is formed by the publications whose objective was to examine the research collaboration patterns across countries. Since international S&T collaboration has become a critical innovation strategy and major theme in many countries, a

growing interest in this topic resulted in a host of bibliometric studies with an attempt to characterize the extent of IRC by introducing a series of indexes or metrics (e.g., Garg and Padhi, 2001; Glänzel and Winterhager, 1992; Nagpaul, 1999). At the early phase, scholars only employed a simple indicator, namely, the amount of international co-authored documents, to characterize the patterns of IRC (e.g., Frame and Carpenter, 1979). Since the 1990s, some scholars established or introduced a series of indicators such as Salton's Index (Glänzel and Winterhager, 1992), International Collaboration Index (Garg and Padhi, 2001), Multilateral Collaboration Index (Glänzel and de Lange, 1997; de Lange and Glänzel, 1997), to analyze the IRC patterns. However, these studies suffered from a crucial limitation, that is, the research findings varied with different methodologies used for characterizing the IRC patterns, which even led to conflicting findings in some scenarios. In this context, the comparison of measurement methods has been presented by some studies such as Luukkonen et al. (1993), which attempted to elaborate the status of quantitative approaches adopted by IRC studies. This study concluded that two kinds of quantitative measures, namely, absolute and relative ones, should be introduced simultaneously for an in-depth analysis of IRC across countries. Later, compared with prior studies discussed above, Glänzel and de Lange (2002) presented a rather simple statistical model for characterizing the international collaboration patterns in science. Tan et al. (2015) implemented a comparative assessment of research performance which resulted from domestic and international research collaboration in Malaysia. The methodology used by Tan et al. (2015) may also prove beneficial for assessing the present and potential state of international collaboration in the context of developing nations.

Furthermore, a number of studies have investigated IRC patterns at different levels. For example, Schubert and Braun (1990) and Gazni et al. (2012) analyzed the patterns of research collaboration across all countries in the world. These studies contributed to deep understanding of the dynamics of IRC at the global level. Some studies investigated this topic at the regional level. For example, Braun and Glaenzel (1996) analyzed the change of annual international co-authorship patterns of five countries in Eastern Europe. Some scholars attempted to identify the collaborative patterns between some major countries. For instance, Leclerc and Gagné (1994) sought to describe the patterns of IRC across three major economies with assistance of bibliometric indicators. Zitt et al. (2000) described the IRC profiles of the top 5 countries in the scientific research field (i.e., USA, United Kingdom, France, Japan and Germany). Garg and Padhi (2001) identified the co-authorship patterns among 14 countries by using some collaborative indexes. Vakilian et al. (2015) investigated the characteristics of collaborative links among the most productive countries in lab-on-a-chip research domain. In addition, some studies explored IRC property at the level of discipline (e.g., Glänzel and de Lange, 2002; Wagner, 2005).

It is noteworthy that the case study on a particular country's research collaboration with other countries has attracted increasing academic interest in recent years. For example, Hayati and Didegah (2010) sought to explore the IRC relationships that Iranian scholars formed with their counterparts from other countries. Tang and Shapira (2011) examined the R&D collaboration between China and USA in the nanotechnology domain. Hu et al. (2012) tried to investigate the patterns of international collaboration in Canadian nanotechnology research. Niu and Qiu (2014) studied China's IRC with other countries from different perspectives. Zhou and Lv (2015) also implemented a case study on research collaboration between China and Germany in the physics domain. Most of these studies provided important insights into the features of IRC relationships of a particular country with other countries, and presented some policy implications for this particular country in terms of international R&D exploitation.

Overall, the studies in the second (green) cluster mainly focused on the characterization of IRC patterns. The techniques used in these studies have changed from a simple count of international publications at the early phase to developing a series of indicators or statistical models for characterizing the IRC patterns effectively. Moreover, the IRC patterns among all countries or core (important) countries, or that of a particular country with other countries, are the major themes of the studies in this cluster. In particular, a particular country's IRC with other countries has attracted increasing attention from scholars in recent years.

5.3. IRC effects

As illustrated in Figure 8 and Table 6, the third (purple) cluster is dominated by the publications that focused on the effects of IRC. It is generally accepted that IRC is always considered as a "good thing" because it not only offers access to scarce or unique resources in other countries (Zhao et al., 2013) but also provides a means to seek complementary capabilities (Beaver and Rosen, 1979; Wagner and Leydesdorff, 2005).

In this context, many scholars examined the effects of IRC. For example, Ma and Guan (2005) examined the effects of IRC in the Molecular Biology field and presented evidence that there was a positive relationship between IRC and research quality in the case of China. Hayati and Didegah (2010) aimed to investigate the impact of IRC on the visibility of papers. Zhou and Lv (2015) found that China–Germany bilateral collaboration in the physics domain significantly enhanced the research performance of both countries.

Although previous studies have shown that the citation frequencies received by domestic co-authored documents were significantly fewer than those received by international co-authored documents (Katz and Martin, 1997; Levitt and Thelwall, 2009), thereby concluding that IRC

provided an opportunity to increase the prestige or visibility of research outputs (Sooryamoorthy, 2009; Schmoch and Schubert, 2007; Narin et al., 1991), it remained unclear whether this phenomenon resulted from IRC or other reasons. In other words, it is still debatable as to whether the quality of scientific outputs is positively associated with the event of IRC when the countries and fields are controlled (Persson, 2010). This promoted Tang (2013) to explore the relationship between research quality and IRC, and this study showed that the research quality was positively affected by IRC, particularly by the collaboration with the high-performing countries such as the USA. However, Sooryamoorthy (2009) found that IRC was not a guarantee for enhancing the citation impact of papers in the case of some disciplines, such as psychiatry, biochemistry, agriculture and material sciences. This indicates that IRC is not always "a good thing".

By and large, the topic regarding the impact of IRC on research performance has drawn great interest from scholars. Some studies gave substantial evidence that research performance was affected by IRC in a positive manner, whereas some studies presented that a positive impact of IRC on research performance in not guaranteed, indicating that the findings on the effects of IRC are still controversial in academia. In fact, IRC not only brings benefits but also entails various costs. However, with the exception of several studies such as Katz and Martin (1997), Landry and Amara (1998), Cummings and Kiesler (2007), He et al. (2009), the costs of IRC are rarely examined in the literature.

5.4. IRC networks

The fourth (yellow) cluster shown in Figure 8 is constituted by the publications on IRC networks. We found that Newman (2001) was the most influential study in this cluster. Besides, another of Newman's works, namely, Newman (2004), was also a prominent study in this cluster. As is broadly known, Newman is one of the earliest researchers who introduced social network analysis (SNA) to investigate research collaboration across countries and made major contributions to revealing the scale-invariant nature and fractal features of research collaboration networks[8].

Prior to the 21st century, there was a substantial body of literature dealing with IRC patterns, their determinants and impacts. However, the studies that were devoted to mapping and analyzing IRC network structure are still scant. Nowadays, due to the appearance of modern computers with enormous computing power and data storage, the rapid development of the internet, and the availability of digital libraries, it becomes possible to accurately depict the topological properties of large-scale networks (Kumar and Jan, 2014). In this context, Newman (2001) first introduced SNA

[8] The authors thank an anonymous reviewer for giving an insightful comment on Newman's contributions to deepening understanding of scale-invariant properties of research collaboration networks.

to precisely chart and inspect the topological structure of international scientific collaboration networks. Similarly, Newman (2004) explored the topological structure of three IRC networks to reveal some interesting network properties. Ever since the pioneering works by Newman that opened the floodgates for IRC network studies (Kumar, 2015), this topic has been investigated extensively in diverse ways. For instance, Wagner and Leydesdorff (2005) investigated international co-authored networks and demonstrated that the growth of international scientific collaboration networks between 1990 and 2000 could be ascribed to self-organizing phenomena, thus this study presented some new explanations for the growth of IRC. Apart from investigating the dynamic mechanism of IRC networks, many studies focused on the topological properties of IRC networks (e.g., Chinchilla-Rodríguez et al., 2012; Niu and Qiu, 2014; Vakilian et al., 2015), which help deepen our understanding of some important issues, such as, "who are the most 'core countries' engaged in IRC networks", "what about the level of knowledge diffusion within a given IRC network" and " what is the influence mechanism between IRC and productivity" (Kumar and Jan, 2014).

In fact, by investigating the structure of research collaboration networks, we can identify the regularity of research collaboration among network nodes (Owen-Smith et al., 2002) and locate the key researchers, institutions and countries participating in international collaboration in the S&T field (Morel et al., 2009). However, understanding IRC from the lens of social networks is still a fairly young research area, and we still have an incomplete understanding on the scale-invariant or fractal features of IRC networks. Moreover, current IRC network studies have been mostly based on "static" data (e.g., Chinchilla-Rodríguez et al., 2012; Niu and Qiu, 2014; Vakilian et al., 2015). There is a need to analyze dynamic data across a time-series in order to get a "longitudinal" perspective in future studies, which could help reveal the dynamics of node decay and the formation of new connections in the IRC network over a time period.

5.5. IRC measurement

The fifth (red) cluster shown in Figure 8 and Table 6 is focused on the validity of adopting co-authored data to measure IRC (e.g., Melin and Persson, 1996; Laudel, 2002; Katz and Martin, 1997). The co-authorship as a measure of research collaboration is a popular approach in the IRC research domain. Prior to the 1970s, the use of questionnaire data to examine IRC in a particular field (such as hydrography, radio and clinical medicine fields) was widely adopted in early studies. However, it is hard to detect the interactions between collaborators with the assistance of commonly used methodologies including questionnaire, interviews and observation. This is largely due to the intricate nature of mutual interactions between the actors (Subramanyam, 1983). So, the collaboration measurement is difficult to achieve by using the traditional methods discussed above.

In the late 1950s and the earlier 1960s, some scholars had observed that the growth of multiple-author publications was correlated with the increment of research collaboration between actors (e.g., Price 1963; Smith, 1958). However, it was not until the late 1970s that Frame and Carpenter (1979) and Beaver and Rosen (1978, 1979) introduced international co-publications as a proxy for measuring research collaboration activities across countries. Since the 1990s, the use of co-authorship data to examine IRC became abundant (e.g., Luukkonen et al., 1993; Moed et al., 1991; Narin et al., 1991; Schubert and Braun, 1990); this is largely due to their perceived objectivity, inexpensive costs, and large-scale availability. In addition, the innovative collaboration forms have extended from the early activities such as mutual visiting, technology import and training to current activities such as joint research, co-building R&D entities and joining technology alliances (Duan, 2011). Accordingly, an important output of research collaboration activities is the co-authored publications. So, the co-publications are widely considered as reliable indicators for reflecting IRC relationships between countries.

Even though the bibliometric analysis of co-authored publications has become a popular approach for revealing the structure and change of international collaboration relationships, a critical issue to be addressed is to what extent the co-authored publications can mirror the actual international collaborations. We acknowledge that the co-authorship relationship is the most formal indicator of collaborative activities among the researchers. However, some kinds of research collaborations do not result in co-authored publications and reversely some co-authored publications cannot mirror the actual situation of research collaborations. In this context, some influential studies in this cluster, such as Melin and Persson (1996), discussed the relationship between the co-authorship reflected by documents and the actual research collaboration. They stressed that, for example, co-authorship data are not capable of revealing the panorama of research collaboration as well as the motivations behind various forms of research collaboration. Similarly, Katz and Martin (1997), the other influential work in this cluster, also discussed the reliability and validity of adopting co-authorships as the proxy for research collaboration. They argued that the complex nature of research collaboration was perhaps not fully characterized by co-authored data alone. Later, Laudel (2002) stressed the co-authored document was just one of many outcomes resulted from research collaboration. In other words, the co-authored data could be deemed as the filter on the multitude of research collaboration relations. Thus, bibliometric analysis of international co-authorship documents should be adopted as the partial index reflecting IRC activities between the countries. In particular, the research collaboration can be accurately depicted based on co-authored data only when all authors affixed to a publication were the actual participants in the research project (Katz and Martin, 1997).

In spite of the limitation of co-authorship measurement, the approach indeed enjoys some merits. Firstly, it is objective and verifiable. In other words, any researchers could reproduce the same results if they have access to the same data sets. Second, it is an inexpensive and practical way to quantify research collaboration. Third, co-authorship data are available from big databases such as Web of Science and Scopus. So, this means that the research samples are very large when using co-authorship measurement and the research findings should be more robust compared with those from case-study (Katz and Martin, 1997; Subramanyam, 1983). Last, given that research collaboration likely results in co-authored publications, international co-authorship data can be considered as a rough indicator of IRC, as long as we tolerate a certain level of potential errors.

Consequently, when the international co-authorship data are used as the proxy for IRC, other kinds of data source should be collected to decrease the potential uncertainties or biases involved. For example, Melkers and Kiopa (2010) examined IRC ties based on the data from a social-network-based survey of scholars from the USA, which showed that this methodology can capture multiple dimensions of research collaborations and related information that are not accessible through bibliometric analysis.

6. Topics for future research

Based on a comprehensive review of IRC studies in the sections above, we have identified some potential or not fully explored topics for the IRC research in this section, which are presented as follows:

6.1 Developing effective measurements of IRC activities

A basic important issue in IRC studies is how to effectively characterize IRC activities, which has always been the focus of extant literature (Katz and Martin, 1997; Laudel, 2002; Melkers and Kiopa 2010). However, as confirmed by the co-citation network analysis (as shown in Figures 2 and 3), the co-authorship analysis to measure IRC has become one of the favorite methods in this research field. IRC was simply equated with the international co-authorship in much IRC research, especially in recent studies (e.g., Li and Li, 2015; Niu and Qiu, 2014; Tan et al., 2015). Even though co-authorship analysis affords a deep insight into the characteristics of multi-national relations in the S&T field, it should be noted that IRC activities sometimes demonstrate more complex and heterogeneous features, which may challenge IRC characterization based on co-authorship indicators alone (Glänzel, 2001). This has been pointed out by some studies in the “red” cluster shown in Figure 8 (such as Melin and Persson, 1996; Laudel, 2002; Katz and Martin, 1997), which clarified the relationships between co-authorship and IRC, and argued that research collaboration did not

necessarily result in a jointly published literature and conversely. Thus, there is an increasing need to clarify the validity of the bibliometric approach for exploring actual IRC. When adopting international co-authorships as the proxy for research collaboration across countries, it is important to consider what they can reflect and what type of international collaboration they cannot identify. However, this topic has been ignored by many studies in the IRC research domain.

In fact, the co-authored publications do not possess enough information that can present an overall view for the process of research collaboration (Lundberg et al., 2006). When adopting international co-authorships to measure research collaboration among countries, we may run a risk of neglecting some collaborative activities that do not result in co-authored publications (Melin and Persson, 1996). In other words, co-authorship is a partial or imperfect proxy for IRC. This suggests that we should gather other data sources or complementary information to reduce the biases and uncertainties involved (Melin and Persson, 1996). Moreover, international co-authorship data cannot provide enough information for revealing the social dynamics behind IRC. Hence, an alternative methodology for effectively characterizing IRC is yet to be formed.

6.2. Exploring the underlying reasons of the country-cross differences of IRC benefits

There has been extensive research on the benefits of IRC, which has demonstrated that countries normally gain benefit from the multi-national S&T collaboration, including: 1) accessing to available ideas, knowledge, technologies and other resources (Hayati and Didegah, 2010; Kim, 2006); 2) time saving resulted from expediting the research process (Hayati and Didegah, 2010); 3) sharing research cost of large scale research projects (Hayati and Didegah, 2010); 4) increasing the visibility (citation rates) of research outputs (Gazni et al., 2012). But do all countries derive these benefits in equal manner? What are the potential factors influencing these benefits that the countries get from IRC?

Recent studies in one cluster (i.e., the “purple” cluster in Figure 8) that focused on this topic showed that IRC was not always a “good thing” for some countries. For instance, Zhou et al. (2013) showed that China did not get any benefits from the collaboration with Japan. Tang (2013) found that the research quality of China is not affected by its collaboration with the USA (Tang, 2013). Bote et al. (2013) confirmed the benefit that the countries got from IRC was not uniform. Why? It is necessary to investigate the reasons for this differentiation by country. However, there have been few attempts to investigate this topic.

6.3. Investigating factors and mechanisms that affecting IRC outcome

Based on bibliographic coupling analysis and main path analysis, we find that the impact of IRC

on research performance has been generally investigated by prior research, especially by recent studies (e.g., Hayati and Didegah, 2010; Tang, 2013; Zhou and Tian, 2014). However, there is still controversy on this topic despite a large amount of research findings from current studies (Li and Shapira, 2012).

On the one hand, many studies have presented evidence that IRC leads to high research performance. For example, Chinchilla-Rodríguez et al. (2012) showed that IRC exerted a positive effect on both research outputs and citations in the biomedical science domain. Sin (2011) confirmed that IRC could significantly enhance the citation counts received by publications in the research domain of library and information. Abramo et al. (2011) demonstrated that Italian university researchers got benefits from IRC. Persson (2010) found that IRC publications have a higher impact compared with non-IRC ones. Similar findings were also found in some notable studies such as Abbasi et al. (2011), Barjak and Robinson (2008) and He et al. (2009).

On the other hand, conflicting evidence has been reported, too, indicating the debate on whether IRC activities raise research performance still exists (Zhou and Tian, 2014). For instance, Leimu and Koricheva (2009) showed that IRC had no effect on the visibility of research outputs. Duque et al. (2005) made a comparative study and found that IRC was not associated with the improvement of research productivity in the context of developing countries. Using panel publication data from more than 100 important USA universities, Adams et al. (2004) confirmed the existence of trade-off impact that IRC exerted on research quantity and quality. Specifically, IRC had a positive relation to research visibility but a negative relation to research productivity.

Overall, an expanding body of studies has explored the effects that IRC exerts on research performance, but the research results are still inconclusive. Why? In our opinion, the factors and mechanisms that may affect IRC's impact on research performance needs to be investigated. However, to our knowledge, few studies have devoted attention to this topic so far.

6.4. Revealing the causality between IRC and high research quality

Based on bibliographic coupling analysis (i.e., the "purple" cluster in Figure 8) as well as main path analysis (as shown in Figure 6), we find that prior research had paid considerable attention to the relationship between IRC and research quality (e.g., Abbasi et al., 2011; Barjak and Robinson, 2008; Abramo et al., 2011; He et al., 2009). Most previous studies argued that the IRC can improve the quality of research findings, rather than the reverse. However, a recent study by Tang (2013) pointed out that most previous studies neglected this possibility: the countries that had a chance to jump into IRC probably represented an elite group with a high level of research capabilities. Even without IRC, those elite countries likewise have higher research performance than others. So, the

positive relationship between IRC and research performance, as Fleming and Chen (2007) noted, is likely subjected to "reverse causality and survivor bias".

The assumed logic adopted by most studies is as follows: the event of IRC is conducive to idea fertilization, which is a basic prerequisite for producing a "good paper" that attracted more scholars' attention and thus is more frequently cited by subsequent literature compared with other papers. Of course, this is beneficial to promote the country's S&T reputation. However, some studies argued that reverse causality might exist. That is, since a country with high S&T reputation is likely to attract other countries to form an IRC relationship with it (Gazni et al., 2012), it is reasonable to deduce that the countries that have a chance to participate in IRC are generally those high-performing ones, suggesting that IRC is just the feedback from the elite countries with high level of S&T capacities. Based on this view, it is not surprising to find that the quantity and quality of publications that result from IRC is higher than those from non-IRC. So, higher research performance should not be solely attributed to a positive effect resulting from IRC.

In order to avoid research bias, the effect of elite countries should be controlled in the testing of the full dataset. In this manner, we can avoid the possibility of bias. However, with the exception of Tang (2013), similar studies remain scarce. Moreover, by combining two inverse logics discussed above, we deduced that there may be an underlying bidirectional relationship between IRC and high research quality. In other words, IRC leads to high research quality and, in turn, countries with high research quality tend to jump into IRC. However, existing literature ignores the possibility that IRC and high research quality may mutually influence each other, which has not been examined so far. This research gap indicates a direction for future research.

6.5. Comparing the difference between scientific and technological collaborations

Our review suggests that most studies focused on international scientific collaboration rather than international technological collaboration, and this trend will continue, as evidenced by a large amount of recent works (e.g., Vakilian et al. 2015; Niu and Qiu, 2014; Li and Li, 2015; Tan et al., 2015). Why? In our opinion, apart from the fact that the large bibliographic data of international scientific collaboration are more available from big databases such as Scopus and Web of Science publication database, the other important reason is that the international scientific collaboration is more prone to occur across national borders, compared with international technological collaboration (Ponds, 2009). This is due to the difference between science and technology in underlying application, direction, norms and values. More specifically, the goal of scientific collaboration is to produce new scientific knowledge and to enhance the scientific discourse, while the goal of technological collaboration is to exploit scientific knowledge for the development of new products

and goods and to minimize knowledge diffusion (Ponds, 2009).

The increasingly important role that intellectual property rights play for benefiting the countries in the process of international trade may result in their conflicts of interest in the S&T field (Mowery, 1998). For example, developing or emerging countries involved in international S&T collaboration could appropriate knowledge or technology that originated from the research projects funded by developed countries. This can lead to asymmetrical benefits in IRC by privileging developing countries over developed countries. So, some elite countries are likely to take action to minimize knowledge or technology diffusion through the channel of international S&T collaboration. For example, USA and EU policymakers restrict China in their military R&D programs. However, compared with international technological collaboration, international scientific collaboration may be less restrained by national boundaries. This is due to the common incentive structure and the 'universal' norms of science (Ponds, 2009). Given the potential conflicts between national policies of protecting intellectual property rights and the increasing IRC, it seems there is some difference between international scientific collaboration and international technological collaboration under the influence of this potential conflict. However, little attention is devoted to this interesting topic in existing literature.

6.6. Investigating inherent properties of IRC collaboration networks

As mentioned earlier, the research on IRC from a social network perspective is still at the fermentation phase. In contrast, the study of complex systems, in particular the complex collaboration networks, has grown very rapidly. It should be noted that the research on scale-invariant or fractal features of collaborative networks, a common characteristic of a complex innovation system (Katz, 2016), has been the focus of intense investigation over the past 20 years. For example, Barabási and Albert (1999) addressed the fractal nature of collaborative networks and enjoy high impact in the research domain of complex innovation systems. Clauset et al. (2009) developed a robust method for determining whether citation distribution demonstrates fractal feature in collaborative networks. Ronda-Pupo and Katz (2016, 2017) revealed the scale-invariant nature of research collaboration.

In fact, the research frame and methodology used in the studies of complex innovation networks, such as Ronda-Pupo and Katz (2016, 2017) and Archambault (2011), can present a valuable perspective for exploring the inherent properties of IRC collaboration networks, including the scale-invariant, fractal features and other characteristics. These interesting issues should be addressed in future studies because such endeavor will facilitate our better understanding of the scale-invariant nature and fractal features of IRC networks.

6.7. Developing a more symmetrical approach to assess the potential costs and benefits of IRC

With the assistance of bibliographic coupling analysis (i.e., the "purple" cluster in Figure 8), we find that a large number of studies have demonstrated a positive correlation between IRC and an article's quality as measured by the number of citations it receives from other articles (Ma and Guan, 2005; Hayati and Didegah, 2010; Zhou and Lv, 2015), suggesting that IRC is beneficial for increasing the visibility of articles. However, as Katz and Martin (1997) noted, while IRC expands the scope of combinatorial search by bringing together diverse ideas and resources from other countries, it also entails some costs which should not be neglected. When two or more countries are collaborating, there is often the problem of reconciling the conflicts resulting from different cultures, linguistics, institutions (i.e., rules on intellectual property rights) and so on. These potential differences need to be reconciled and more endeavors are devoted to monitoring, enforcing, and renegotiating IRC. Moreover, IRC incurs additional costs relative to local RC, especially in terms of coordinating research carried out at geographically dispersed locations and possibly extra time for travelling and visiting. Therefore, IRC is subject to various costs for bridging geographic distances and institutional differences (Hinds and Bailey, 2003; Adams et al., 2005; Cummings and Kiesler, 2007).

In fact, IRC brings significant costs as well as undoubted benefits. Even though there has been a growing belief that the benefits of IRC outweigh its costs, we must recognize that, in some circumstances, the costs may very well outweigh the benefits (Katz and Martin, 1997). So, we should identify the main benefits from collaboration and the associated costs as well. Unfortunately, at present there is no means of systematically appraising all the costs and benefits of collaboration, and therefore no way of establishing whether the benefits do actually outweigh the costs. In future, we would argue, a more symmetrical approach should be developed to assess the potential costs and benefits. This is helpful for policymakers to re-examine whether more IRC should be encouraged.

7. Conclusions and discussions

7.1 Research findings

In today's increasingly global competitive period, it is virtually impossible for any single country to stay away from research collaborations with other countries because science, technology and innovation have increasingly become a global and collaborative undertaking. So, IRC is taken as the top priority for many countries. A series of policies and strategies to develop collaborative linkages with other countries for S&T innovation have been introduced. The prevalence of IRC has

attracted the attention of scholars worldwide. Accordingly, IRC studies have grown exponentially. This study attempts to fill the gap in our understanding by providing a systematic and comprehensive review of the growing IRC literature. It investigated the intellectual base, the main research trajectories and the intellectual communities in the IRC research domain. We find that the historical origin of the IRC research field is under the influence of two pioneering works related to bibliometrics research (i.e., Price, 1963; Price and Beaver, 1966). By tracing the main research trajectories in the IRC research domain, we find that the research methodology adopting international co-publication as the proxy of IRC to examine research collaboration across different countries has become a popular research paradigm, even though the validity of this methodology has been queried by some influential studies (e.g., Melin and Persson, 1996; Katz and Martin, 1997). The co-citation network analysis reveals that Katz and Martin (1997), in which a more comprehensive analytical framework for exploring research collaboration is introduced, is the most influential work in this field. Moreover, the bibliographic coupling analysis shows that IRC studies can be categorized into five main research themes, namely, driving factors of IRC, IRC patterns, IRC effects, IRC networks and IRC measurement. Based on a comprehensive review of IRC studies, we also identified seven potential or not fully explored topics for potential future research on IRC.

7.2 Implications for theory and practice

This comprehensive review of IRC studies not only provides a better understanding of this research domain, but also presents important implications for future research. The mainstream approach in IRC studies using international co-publication as a proxy of IRC relations has been criticized by early studies for its validity (e.g., Melin and Persson, 1996; Katz and Martin, 1997). However, an alternative method for effectively characterizing IRC activities is still yet to be formed – this is a significant gap that requires urgent research attention. In addition, a large number of studies have focused on the benefits of IRC. However, very little literature has examined the costs of IRC. In fact, IRC demonstrates dual effects (benefits and costs). So, we should identify the main benefits from collaboration and the associated costs as well. Unfortunately, at present there is no means of systematically appraising all the costs and benefits of collaboration, and therefore no way of establishing whether the benefits do actually outweigh the costs. In future, we would argue, a more symmetrical approach should be developed to assess the potential costs and benefits. Moreover, although an expanding body of studies has focused on the effects of IRC, relatively few studies shed new light on some important issues including: what are the potential factors influencing these benefits that different countries and organizations get from IRC? What are the factors and mechanisms that affect the impact of IRC on research performance? Is there a one-way or two-way

relationship between IRC and high research quality? What is the scale-invariant nature and fractal features that IRC network exhibits? These gaps shed useful insights for future research in this area.

This paper also has important practical implications for policy makers. After implementing a systematic overview of IRC literature, we find that most previous studies have confirmed that the countries participating in IRC are placed in advantageous positions to promote S&T advancement (Wang et al., 2014) and therefore result in better innovative competitive advantages. This suggests that policy makers should take effective measures to intensify collaborative linkages with other countries in the S&T field. It should be noted that not all countries can derive the same benefit from IRC. Compared with the developed countries such as the USA, developing countries can gain more from IRC (Bote et al., 2013). This indicates that policy makers of developing countries should launch relevant policies and strategies to strengthen multi-national collaborations with these developed countries in the S&T field in order to take advantage of R&D resources from them. Moreover, due to asymmetric benefits of IRC between the developing and developed countries, developed countries are likely to take action to restrict developing countries in their S&T programs. Given the common incentive structure as well as the 'universal' norms of science, international collaboration in the scientific field is likely to be less restrained by national borders compared with international collaboration in the technological field. Accordingly, the scientific collaborations tend to occur most frequently across national borders while the technological collaborations between enterprises are less likely to take place at the international level (Ponds, 2009). This implies that developing countries should develop more scientific collaborative linkages with developed countries for S&T innovation, which may bypass the national policies of protecting intellectual property rights implemented by developed countries.

7.3 limitations

Although we tried to make the literature review as comprehensive as possible, our analysis is subject to several limitations. Firstly, although the WOS database is one of the most complete sources of scientific publications and includes the majority of important journals, it should be noted that some publications, such as books and the non-English publications, are not completely included in WOS. So the results of our analysis should be treated with caution due to this limitation of the data source. Secondly, this paper introduces the main path analysis to reduce a complicated citation network to one or several simple path(s). Although this helps to capture the main research trajectory of a particular research domain, it only considers a small number of crucial nodes and links in the network, and ignores the less prominent ones such as the studies on the IRC at the firm level due to limited number of studies published using firm-level data. This may lead to omission of such studies

in our findings and conclusions. Thirdly, this paper focuses on IRC research domain, which is a small subset of a broader study on research collaboration. Thus our study only presents the reader with a narrow view of the broader collaboration research and policy landscape in which IRC is embedded. To enrich the research on the larger research landscape regarding S&T collaboration, future studies should broaden their research sample by considering different (individual, organizational) levels of research collaboration as well as complex innovation systems. Finally, we investigate the IRC research domain mainly by means of citation-based analysis, which is widely accepted as a useful and effective tool to identify the core documents with high frequency of being cited by the datasets of publications from a particular research domain. However, some important publications with top citation impacts in the Web of Science are likely to be neglected if those publications are widely cited by difference research domains/disciplines rather than by the IRC research domain. For example, some important studies on complex innovation systems, such as Barabasi and Albert (1999) and Clauset et al. (2009), made major contributions to the understanding of the scale-invariant nature and other characteristics of collaboration networks and received a high citation impact in the research domain of complex systems, in particular complex networks. However, because they are not highly cited by publications from the IRC domain, those crucial studies do not appear in the main research trajectories and intellectual base of IRC research domain. Possible reasons for such phenomenon may be due to, firstly, the techniques that are used in those studies on complex innovation system are not widely mastered by scholars in social sciences such as the IRC research domain; and secondly, they are published in science and engineering journals and hence were screened out in the literature reviews in normal social sciences research.

Appendix A. Definition of search queries for SSCI publications with IRC topic

Based on a review of the core literature from the IRC research field and the suggestions from some experts in this field, we composed a ‘‘pilot query’’ based on a set of terms to search for data from the database. Then we used text mining analysis to extract key attributes and filtered the results to compose a list of candidate terms. Finally, the experts were consulted to screen and modify the candidate terms. The above processes were repeated several times until a convergent result was obtained and re-confirmed by experts. The final terms for the query are shown in Table A1. The time spans from the year 1957 to 2015. This broad search term, however, may capture some papers that had little to do with IRC. To ensure the accuracy of datasets, we therefore screened all literature abstracts carefully to assess whether they focused on IRC. When we were unsure, the full publication were downloaded and examined. Finally, we follow Ronda-Pupo and Katz (2017) to select 1490 publications, including the peer-reviewed document types of Article, Note, Proceedings Paper and Review, to build the final database of this study.

Table A1. The search queries for SSCI publications on IRC topic

Steps	Search strategies	No. of papers
First	#1: TS= (((“research collaboration*”) OR (“R&D collaboration*”) OR (“technology collaboration*”) OR (“S&T collaboration*”) OR (“innovation collaboration*”) OR (“research cooperation*”) OR (“innovation cooperation*”) OR (“technology cooperation*”) OR (“S&T cooperation*”) OR (“R&D cooperation*”)) AND foreign)	67
Second	#2: TS= (((“international cooperation*”) OR (“international collaboration*”)) AND (Research OR Science OR Technology OR S&T OR innovation OR R&D))	1332
Third	#3: TS= (((“multinational cooperation*”) OR (“multinational collaboration*”)) AND (Research OR Science OR Technology OR S&T OR innovation OR R&D))	9
Fourth	#4: TS= ((“international innovative” OR “international innovation”) AND (collaboration* OR cooperation*)) OR TS= ((international OR multinational) AND (“scientific and technological collaboration” OR “scientific and technological cooperation”)) OR TS= (((“research collaboration*”) OR (“research cooperation*”) OR (“R&D collaboration*”) OR (“R&D cooperation*”) OR (“research and development collaboration*”) OR (“research and development cooperation*”) OR (“innovation alliance*”) OR (“innovative alliance*”) OR (“innovation collaboration*”) OR (“innovation cooperation”)) AND (“across countries”)) OR TS= ((“international alliance” OR “multinational alliance”) AND innovation) OR TS= ((“international research collaboration*”) OR (“international research cooperation*”)) OR TS= ((“international S&T collaboration*”) OR (“international S&T cooperation*”)) OR TS= ((“multinational research collaboration*”) OR (“multinational research cooperation*”)) OR TS= ((“international scientific collaboration*”) OR (“international scientific cooperation*”)) OR TS= ((“international R&D collaboration*”) OR (“international R&D cooperation*”)) OR TS= ((“international research and	278

	development collaboration*") OR ("international research and development cooperation*")) OR TS= (("multinational research and development collaboration*") OR ("multinational research and development cooperation*")) OR TS= (("international technological collaboration*") OR ("international technological cooperation*"))	
Fifth	#1 OR #2 OR #3 OR #4	1490

Note: In WOS, "TS" (i.e. topic), relates to four fields, namely, keywords, abstract, title as well as keywords plus. Therefore, a publication with the inquired terms appearing in these four fields is retrieved.

References

Abbasi, A., Altmann, J., Hossain, L., 2011. Identifying the effects of co-authorship networks on the performance of scholars: A correlation and regression analysis of performance measures and social network analysis measures. Journal of Informetrics 5(4), 594-607.

Abramo, G., D'Angelo, C.A., Solazzi, M., 2011. The relationship between scientists' research performance and the degree of internationalization of their research. Scientometrics 86(3), 629-643.

Adams, J., 2012. Collaborations: The rise of research networks. Nature 490(7420), 335-336.

Adams, J.D., Black, G.C., Clemmons, J.R., Stephan, P.E., 2004. Scientific teams and institutional collaborations: Evidence from U.S. universities, 1981–1999. Research Policy 34(3), 259-285.

Adams, J.D., Black, G.C., Clemmons, J.R., Stephan, P.E., 2005. Scientific teams and institutional collaborations: Evidence from U.S. universities, 1981–1999. Research Policy, 34(3), 259-285.

Anuradha, K., Urs, S., 2007. Bibliometric indicators of Indian research collaboration patterns: A correspondence analysis. Scientometrics 71(2), 179-189.

Archambault, É., Olivier H. Beauchesne, Grégoire Côté, and Guillaume Roberge, 2011. Scale-adjusted metrics of scientific collaboration, The 13th Conference of the International Society for Scientometrics and Informetrics (ISSI 2011), Durban, pp. 78-88.

Barabási, A.L., Albert, R., 1999. Emergence of Scaling in Random Networks. Science 286(5439), 509-512.

Barjak, F., Robinson, S., 2008. International collaboration, mobility and team diversity in the life sciences: impact on research performance. Social Geography Discussions 3(1), 23-36.

Batagelj, V., Mrvar, A., 1998. Pajek-program for large network analysis. Connections 21(2), 47-57.

Beaver, D., Rosen, R., 1978. Studies in scientific collaboration: Part I. The professional origins of scientific co-authorship. Scientometrics 1(1), 65-84.

Beaver, D.D., Rosen, R., 1979. Studies in scientific collaboration: Part II. Scientific co-authorship, research productivity and visibility in the French scientific elite, 1799–1830. Scientometrics 1(2), 133-149.

Bhupatiraju, S., Nomaler, Ö., Triulzi, G., Verspagen, B., 2012. Knowledge flows–Analyzing the core literature of innovation, entrepreneurship and science and technology studies. Research Policy 41(7), 1205-1218.

Bleuler, M., 1958. International cooperation in research on schizophrenia. Bulletin of the Menninger Clinic 22(2), 43.

Blondel, V.D., Guillaume, J.L., Lambiotte, R., Lefebvre, E., 2008. Fast unfolding of communities in large networks. Journal of statistical mechanics: theory and experiment 2008(10), 155-168.

Bote, G., Vicente, P., Olmeda‐Gómez, C., Moya‐Anegón, F., 2013. Quantifying the benefits of international scientific collaboration. Journal of the American Society for Information Science and Technology 64(2), 392-404.

Boyack, K.W., Klavans, R., 2010. Co‐citation analysis, bibliographic coupling, and direct citation: Which citation approach represents the research front most accurately? Journal of the American Society for Information Science and Technology 61(12), 2389-2404.

Bozeman, B., Boardman, C., 2014. Research collaboration and team science: A state-of-the-art review and agenda. Tokyo, Japan : Springer.

Braun, T., Glaenzel, W., 1996. International collaboration: Will it be keeping alive East European research? Scientometrics 36(2), 247-254.

Chen, C., 2003. Mapping scientific frontiers. London, UK: Springer.

Chen, K., Guan, J., 2011. A bibliometric investigation of research performance in emerging nanobiopharmaceuticals. Journal of Informetrics 5(2), 233-247.

Chen, Y.B., Liu, J.S., Lin, P., 2013. Recent trend in graphene for optoelectronics. Journal of nanoparticle research 15(2), 1-14.

Chinchilla-Rodríguez, Z., López-Illescas, C., Moya-Anegón, F., 2012. Biomedical scientific publication patterns in the Scopus database: a case study of Andalusia, Spain. Acimed 23(3), 219-237.

Chuang, T.C., Liu, J.S., Lu, L.Y., Lee, Y., 2014. The main paths of medical tourism: From transplantation to beautification. Tourism Management 45, 49-58.

Clauset, A., Shalizi, C.R., Newman, M.E.J., 2009. Power-Law Distributions in Empirical Data. Siam Review 51(4), 661-703.

Cronin, B., Shaw, D., La Barre, K., 2003. A cast of thousands: Coauthorship and subauthorship collaboration in the 20th century as manifested in the scholarly journal literature of psychology and philosophy. Journal of the American Society for Information Science and Technology 54(9), 855-871.

Cummings, J.N., Kiesler, S., 2007. Coordination costs and project outcomes in multi-university collaborations. Research Policy, 36(10), 1620-1634.

Dahlander, L., Gann, D.M., 2010. How open is innovation? Research Policy 39(6), 699-709.

Davids, M., Frenken, K., 2018. Proximity, knowledge base and the innovation process: towards an integrated framework. Regional studies 52(3), 1-12.

de Lange, C., Glänzel, W., 1997. Modelling and measuring multilateral co-authorship in international scientific collaboration. Part I. Development of a new model using a series expansion approach. Scientometrics 40(3), 593-604.

Doré, J.C., Ojasoo, T., Okubo, Y., Durand, T., Dudognon, G., Miquel, J.F., 1996. Correspondence factor analysis of the publication patterns of 48 countries over the period 1981–1992. Journal of the American Society for Information Science 47(8), 588-602.

Duan, L., 2011. Analysis of the relationship between international cooperation and scientific publications in energy R&D in China. Applied energy 88(12), 4229-4238.

Duque, R.B., Ynalvez, M., Sooryamoorthy, R., Mbatia, P., Dzorgbo, D.B.S., Shrum, W., 2005. Collaboration Paradox Scientific Productivity, the Internet, and Problems of Research in Developing Areas. Social Studies of Science 35(5), 755-785.

Feng, F., Zhang, L., Du, Y., Wang, W., 2015. Visualization and quantitative study in bibliographic databases: A case in the field of university–industry cooperation. Journal of Informetrics 9(1), 118-134.

Fleming, L., Chen, D., 2007. Collaborative Brokerage, Generative Creativity, and Creative Success. Administrative Science Quarterly 52(3), 443-475.

Frame, J.D., Carpenter, M.P., 1979. International research collaboration. Social Studies of Science 9(4), 481-497.

Franceschet, M., Costantini, A., 2010. The effect of scholar collaboration on impact and quality of academic papers. Journal of Informetrics 4(4), 540-553.

Fu, X., Li, J., 2016. Collaboration with foreign universities for innovation: Evidence from Chinese manufacturing firms. International Journal of Technology Management, 70(2/3), 193-217.

Garfield, E., 2009. From the science of science to Scientometrics visualizing the history of science with HistCite software. Journal of Informetrics 3(3), 173-179.

Garfield, E., Paris, S.W., Stock, W.G., 2006. HistCite™: A software tool for informetric analysis of citation linkage. NFD Information-Wissenschaft und Praxis 57(8), 391-400.

Garfield, E., Pudovkin, A.I., Istomin, V.S., 2003. Why do we need algorithmic historiography? Journal of the American Society for Information Science and Technology 54(5), 400-412.

Garg, K., Padhi, P., 2001. A study of collaboration in laser science and technology. Scientometrics 51(2), 415-427.

Gazni, A., Sugimoto, C.R., Didegah, F., 2012. Mapping world scientific collaboration: Authors, institutions, and

countries. Journal of the American Society for Information Science and Technology 63(2), 323-335.
Georghiou, L., 1998. Global cooperation in research. Research Policy 27(6), 611-626.
Glänzel, W., 2001. National characteristics in international scientific co-authorship relations. Scientometrics 51(1), 69-115.
Glänzel, W., de Lange, C., 1997. Modelling and measuring multilateral co-authorship in international scientific collaboration. Part II. A comparative study on the extent and change of international scientific collaboration links. Scientometrics 40(3), 605-626.
Glänzel, W., de Lange, C., 2002. A distributional approach to multinationality measures of international scientific collaboration. Scientometrics 54(1), 75-89.
Glänzel, W., Schlemmer, B., 2007. National research profiles in a changing Europe (1983–2003) An exploratory study of sectoral characteristics in the Triple Helix. Scientometrics 70(2), 267-275.
Glänzel, W., Schubert, A., Czerwon, H.-J., 1999. A bibliometric analysis of international scientific cooperation of the European Union (1985–1995). Scientometrics 45(2), 185-202.
Glänzel, W., Winterhager, M., 1992. International collaboration of three East European countries with Germany in the sciences, 1980–1989. Scientometrics 25(2), 219-227.
Gomez, I., Fernandez, M.T., Sebastian, J., 1999. Analysis of the structure of international scientific cooperation networks through bibliometric indicators. Scientometrics 44(3), 441-457.
Hansen, N., 1983. International-cooperation in border regions - an overview and research agenda. International Regional Science Review 8(3), 255-270.
Harirchi, G., Melin, G., Etemad, S., 2007. An exploratory study of the feature of Iranian co-authorships in biology, chemistry and physics. Scientometrics 72(1), 11-24.
Have, v.d.R.P., Rubalcaba, L., 2016. Social innovation research: An emerging area of innovation studies? Research Policy. (In press)
Hayati, Z., Didegah, F., 2010. International scientific collaboration among Iranian researchers during 1998-2007. Library Hi Tech 28(3), 433-446.
He, Z.L., Geng, X.S., Campbell-Hunt, C., 2009. Research collaboration and research output: A longitudinal study of 65 biomedical scientists in a New Zealand university. Research Policy 38(2), 306-317.
Hinds, P., Bailey, D.E., 2003. Out of Sight, Out of Sync: Understanding Conflict in Distributed Teams. Organization Science, 14(6), 615-632.
Hoekman, J., Frenken, K., Tijssen, R.J.W., 2010. Research collaboration at a distance: Changing spatial patterns of scientific collaboration within Europe. Research Policy 39(5), 662-673.
Hu, G., Carley, S., Tang, L., 2012. Visualizing nanotechnology research in Canada: Evidence from publication activities, 1990–2009. The Journal of Technology Transfer 37(4), 550-562.
Hummon, N.P., Dereian, P., 1989. Connectivity in a citation network: The development of DNA theory. Social networks 11(1), 39-63.
Hung, S.-C., Liu, J.S., Lu, L.Y., Tseng, Y.C., 2014. Technological change in lithium iron phosphate battery: the key-route main path analysis. Scientometrics 100(1), 97-120.
Hwang, K., 2007. International collaboration in multilayered center-periphery in the globalization of science and technology. Science, Technology & Human Values 33(1), 101-133.
Jin, J., Wu, Y., Liang, Z., 2007. A summary of bibliometric study on international science and technology cooperation. Libr Inform Serv 51(3), 63-67.
Katz, J.S., 1994. Geographical proximity and scientific collaboration. Scientometrics 31(1), 31-43.
Katz, J.S., 2016. What Is a Complex Innovation System? Plos One 11(6), 1-27.
Katz, J.S., Martin, B.R., 1997. What is research collaboration? Research Policy 26(1), 1-18.

Kessler, M.M., 1963. Bibliographic coupling between scientific papers. American documentation 14(1), 10-25.

Kim, K.-W., 2006. Measuring international research collaboration of peripheral countries: Taking the context into consideration. Scientometrics 66(2), 231-240.

Kumar, S., 2015. Co-authorship networks: A review of the literature. Aslib Journal of Information Management 67(1), 55-73.

Kumar, S., Jan, J.M., 2014. Relationship between authors' structural position in the collaboration network and research productivity: Case of Indian earth scientists. Program 48(4), 355-369.

Lancho Barrantes, B.S., Bote, G., Vicente, P., Rodríguez, Z.C., de Moya Anegón, F., 2012. Citation flows in the zones of influence of scientific collaborations. Journal of the American Society for Information Science and Technology 63(3), 481-489.

Landry, R., Amara, N., 1998. The impact of transaction costs on the institutional structuration of collaborative academic research. Research Policy, 27(9), 901-913.

Laudel, G., 2002. What do we measure by co-authorships? Research Evaluation 11(1), 3-15.

Leclerc, M., Gagné, J., 1994. International scientific cooperation: The continentalization of science. Scientometrics 31(3), 261-292.

Leimu, R., Koricheva, J., 2009. Does Scientific Collaboration Increase the Impact of Ecological Articles? Bioscience 55(5), 438-443.

Levitt, J.M., Thelwall, M., 2009. Citation levels and collaboration within library and information science. Journal of the American Society for Information Science and Technology 60(3), 434-442.

Lewison, G., Cunningham, P., 1991. Bibliometric studies for the evaluation of trans-national research. Scientometrics 21(2), 223-244.

Li, J., Li, Y., 2015. Patterns and evolution of coauthorship in China's humanities and social sciences. Scientometrics 102(3), 1997-2010.

Li, T., Shapira, P., 2012. Effects of international collaboration and knowledge moderation on China's nanotechnology research impacts. Journal of Technology Management in China 7(1), 94-110.

Liu, J.S., Lu, L.Y., 2012. An integrated approach for main path analysis: Development of the Hirsch index as an example. Journal of the American Society for Information Science and Technology 63(3), 528-542.

Liu, J.S., Lu, L.Y., Lu, W.M., 2016. Research fronts in data envelopment analysis. Omega 58, 33-45.

Liu, J.S., Lu, L.Y., Lu, W.M., Lin, B.J., 2013. Data envelopment analysis 1978–2010: A citation-based literature survey. Omega 41(1), 3-15.

Lu, L.Y., Lin, B.J., Liu, J.S., Yu, C.Y., 2012. Ethics in nanotechnology: What's being done? What's missing? Journal of business ethics 109(4), 583-598.

Lu, L.Y.Y., Hsieh, C.H., Liu, J.S., 2016. Development trajectory and research themes of foresight. Technological Forecasting & Social Change 112(1), 347-356.

Lu, L.Y., Liu, J.S., 2014. The knowledge diffusion paths of corporate social responsibility–from 1970 to 2011. Corporate Social Responsibility and Environmental Management 21(2), 113-128.

Lundberg, J., Tomson, G., Lundkvist, I., Brommels, M., 2006. Collaboration uncovered: Exploring the adequacy of measuring university-industry collaboration through co-authorship and funding. Scientometrics 69(3), 575-589.

Luukkonen, T., Persson, O., Sivertsen, G., 1992. Understanding patterns of international scientific collaboration. Science, Technology & Human Values 17(1), 101-126.

Luukkonen, T., Tijssen, R., Persson, O., Sivertsen, G., 1993. The measurement of international scientific collaboration. Scientometrics 28(1), 15-36.

Ma, N., Guan, J., 2005. An exploratory study on collaboration profiles of Chinese publications in Molecular

Biology. Scientometrics 65(3), 343-355.
Martin, B.R., 2012. The evolution of science policy and innovation studies. Research Policy 41(7), 1219-1239.
Melin, G., 1999. Impact of national size on research collaboration: a comparison between northern european and american universities. Scientometrics 46(1), 161-170.
Melin, G., Persson, O., 1996. Studying research collaboration using co-authorships. Scientometrics 36(3), 363-377.
Melkers, J., Kiopa, A., 2010. The social capital of global ties in science: The added value of international collaboration. Review of Policy Research 27(4), 389-414.
Moed, H., De Bruin, R., Nederhof, A., Tijssen, R., 1991. International scientific co-operation and awareness within the European Community: Problems and perspectives. Scientometrics 21(3), 291-311.
Morel, C.M., Serruya, S.J., Penna, G.O., Guimarães, R., 2009. Co-authorship network analysis: a powerful tool for strategic planning of research, development and capacity building programs on neglected diseases. PLoS Neglected Tropical Diseases 3(8).
Mowery, D.C., 1998. The changing structure of the US national innovation system: Implications for international conflict on cooperation and R&D. Research Policy 27(6), 639-654.
Nagpaul, P., 1999. Transnational linkages of Indian science: A structural analysis. Scientometrics 46(1), 109-140.
Narin, F., Stevens, K., Whitlow, E., 1991. Scientific co-operation in Europe and the citation of multinationally authored papers. Scientometrics 21(3), 313-323.
Newman, M.E., 2001. The structure of scientific collaboration networks. Proceedings of the National Academy of Sciences 98(2), 404-409.
Newman, M.E., 2004. Coauthorship networks and patterns of scientific collaboration. Proceedings of the National Academy of Sciences 101(suppl 1), 5200-5205.
Niu, F., Qiu, J., 2014. Network structure, distribution and the growth of Chinese international research collaboration. Scientometrics 98(2), 1221-1233.
Niu, X.S., 2014. International scientific collaboration between Australia and China: A mixed-methodology for investigating the social processes and its implications for national innovation systems. Technological Forecasting and Social Change 85, 58-68.
Owen-Smith, J., Riccaboni, M., Pammolli, F., Powell, W.W., 2002. A comparison of US and European university-industry relations in the life sciences. Management Science 48(1), 24-43.
Persson, O., 1994. The intellectual base and research fronts of “jasis” 1986-1990. Journal of the American Society for Information Science 45(1), 31-38.
Persson, O., 2010. Are highly cited papers more international? Scientometrics 83(2), 397-401.
Plotnikova, T., Rake, B., 2014. Collaboration in pharmaceutical research: exploration of country-level determinants. Scientometrics 98(2), 1173-1202.
Ponds, R., 2009. The limits to internationalization of scientific research collaboration. Journal of Technology Transfer 34(1), 76-94.
Ponds, R., Oort, F.V., Frenken, K., 2007. The geographical and institutional proximity of research collaboration. Papers in Regional Science 86(3), 423-443.
Price, D.D.J., Beaver, D., 1966. Collaboration in an invisible college. American psychologist 21(11), 1011-1018.
Price, D.d.S., 1963. Big science, little science. Columbia University, New York, 119-119.
Ronda-Pupo, G.A., Katz, J.S., 2016. The scaling relationship between citation-based performance and international collaboration of Cuban articles in natural sciences. Scientometrics 107(3), 1423-1434.
Ronda-Pupo, G.A., Katz, J.S., 2017. The Scaling Relationship Between Citation-Based Performance and Coauthorship Patterns in Natural Sciences. Journal of the Association for Information Science and Technology 68(5), 1257-1265

Salton, G., McGill, M.J., 1983. Introduction to modern information retrieval. McGraw-Hill, Auckland.

Schildt, H.A., Zahra, S.A., Sillanpää, A., 2006. Scholarly communities in entrepreneurship research: a co‐citation analysis. Entrepreneurship Theory and Practice 30(3), 399-415.

Schmoch, U., Schubert, T., 2007. Are international co-publications an indicator for quality of scientific research? Scientometrics 74(3), 361-377.

Schubert, A., Braun, T., 1990. International collaboration in the sciences 1981–1985. Scientometrics 19(1-2), 3-10.

Sharma, S., Thomas, V., 2008. Inter-country R&D efficiency analysis: An application of data envelopment analysis. Scientometrics 76(3), 483-501.

Sin, S.C.J., 2011. Longitudinal Trends in Internationalisation, Collaboration Types, and Citation Impact: A Bibliometric Analysis of Seven LIS Journals (1980-2008). Journal of Library & Information Studies 9(1), 27-49.

Small, H., 1973. Co-citation in the scientific literature: A new measure of the relationship between two documents. Journal of the Association for Information Science and Technology 24(4), 265‐269.

Smith, M., 1958. The trend toward multiple authorship in psychology. American psychologist 13(10), 596-599.

Sooryamoorthy, R., 2009. Do types of collaboration change citation? Collaboration and citation patterns of South African science publications. Scientometrics 81(1), 177-193.

Subramanyam, K., 1983. Bibliometric studies of research collaboration: A review. Journal of Information Science 6(1), 33-38.

Tan, H.X., Ujum, E.A., Choong, K.F., Ratnavelu, K., 2015. Impact analysis of domestic and international research collaborations: a Malaysian case study. Scientometrics 102(1), 885-904.

Tang, L., 2013. Does “birds of a feather flock together” matter—Evidence from a longitudinal study on US–China scientific collaboration. Journal of Informetrics 7(2), 330-344.

Tang, L., Hu, G., 2013. Tracing the footprint of knowledge spillover: Evidence from US–China collaboration in nanotechnology. Journal of the American Society for Information Science and Technology 64(9), 1791-1801.

Tang, L., Shapira, P., 2011. China–US scientific collaboration in nanotechnology: Patterns and dynamics. Scientometrics 88(1), 1-16.

Vakilian, M., Majlis, B.Y., Mousavi, M., 2015. A bibliometric analysis of lab-on-a-chip research from 2001 to 2013. Scientometrics 105(2), 789-804.

Verspagen, B., 2007. Mapping technological trajectories as patent citation networks: A study on the history of fuel cell research. Advances in Complex Systems 10(01), 93-115.

Wagner, C.S., 2005. Six case studies of international collaboration in science. Scientometrics 62(1), 3-26.

Wagner, C.S., 2009. The new invisible college: Science for development. Brookings Institution Press, Washington, DC.

Wagner, C.S., Leydesdorff, L., 2005. Network structure, self-organization, and the growth of international collaboration in science. Research Policy 34(10), 1608-1618.

Wang, X., Huang, M., Wang, H., Lei, M., Zhu, D., Ren, J., Jabeen, M., 2014. International Collaboration Activity Index: Case study of dye-sensitized solar cells. Journal of Informetrics 8(4), 854-862.

Wang, X., Xu, S., Liu, D., Liang, Y., 2012. The role of Chinese–American scientists in China–US scientific collaboration: A study in nanotechnology. Scientometrics 91(3), 737-749.

Wang, X., Xu, S., Wang, Z., Peng, L., Wang, C., 2013. International scientific collaboration of China: Collaborating countries, institutions and individuals. Scientometrics 95(3), 885-894.

Watt, W.G., 1957. International-cooperation in the science of hydrography. Department of state bulletin 37(948), 361-363.

Wei, F., Grubesic, T.H., Bishop, B.W., 2015. Exploring the GIS knowledge domain using CiteSpace. The

Professional Geographer 67(3), 374-384.
Welpe, I.M., Wollersheim, J., Ringelhan, S., Osterloh, M., 2015. Incentives and performance. Switzerland: Springer.
Wilsdon, J., 2011. Knowledge, networks and nations: Global scientific collaboration in the 21st century. UK: the Royal Society.
Yu, D., Shi, S., 2015. Researching the development of Atanassov intuitionistic fuzzy set. Applied Soft Computing 25(C), 189-198.
Zhai, L., Yan, X., Shibchurn, J., Song, X., 2014. Evolutionary analysis of international collaboration network of Chinese scholars in management research. Scientometrics 98(2), 1435-1454.
Zhao, X.G., Yang, Y.S., Feng, T.T., Yang, Y.H., 2013. International cooperation on renewable energy electricity in China–A critical analysis. Renewable energy 55, 410-416.
Zheng, J., Zhao, Z.Y., Zhang, X., Chen, D.-Z., Huang, M.H., Lei, X.P., Zhang, Z.Y., Zhao, Y.H., 2011. International scientific and technological collaboration of China from 2004 to 2008: a perspective from paper and patent analysis. Scientometrics 91(1), 65-80.
Zhou, P., Glänzel, W., 2010. In-depth analysis on China's international cooperation in science. Scientometrics 82(3), 597-612.
Zhou, P., Lv, X., 2015. Academic publishing and collaboration between China and Germany in physics. Scientometrics 105(3), 1875-1887.
Zhou, P., Tian, H., 2014. Funded collaboration research in mathematics in China. Scientometrics 99(3), 695-715.
Zhou, P., Zhong, Y., Yu, M., 2013. A bibliometric investigation on China–UK collaboration in food and agriculture. Scientometrics 97(2), 267-285.
Zitt, M., Bassecoulard, E., Okubo, Y., 2000. Shadows of the past in international cooperation: Collaboration profiles of the top five producers of science. Scientometrics 47(3), 627-657.