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Scientific collaboration and high-technology exchanges among BRICS and G-7 countries

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Abstract Over the last two decades, emerging countries located outside North America and Europe have reshaped the global economy. These countries are also increasing their share of the world's scientific output. This paper analyzes the evolution of BRICS (Brazil, Russia, India, China and South Africa) and G-7 countries' international scientific collaboration, and compares it with high-technology economic exchanges between 1995–1997 and 2010–2012. Our results show that BRICS scientific activities are enhanced by their high-technology exports and, to a larger extent, by their international collaboration with G-7 countries which remains, over the period studied, at the core of the BRICS scientific collaboration network. However, while high-technology exports made by most BRICS countries to G-7 countries have increased over the studied period, both the intra-BRICS high-technology flows and the intra-BRICS scientific collaboration have remained very weak.

Keywords G-7 · BRICS · Scientific collaboration · High-technology · Economic cooperation

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Introduction

Over the last two decades, emerging countries located outside North America and Europe have shown high economic growth rates. Many analysts thus predict that the world's economic center of gravity will shift from Western countries, namely G-7 countries (Canada, France, Germany, Italy, Japan, UK and USA), to emerging countries such as those from Southeast Asia and Latin America (Klein 2009; Grether and Mathys 2010; Kharas 2010; OECD 2010; Quah 2011; Klein and Salvatore 2013). These economic transformations might be associated with a similar shift of the science and technology center of gravity, and scientific collaboration might play an important role in such changes. The BRIC Association, formed originally by Brazil, Russia, India and China, became official in 2009, with the aim of improving its global economic situation by co-operation among the four countries (BBC 2009). In 2011, South Africa joined the association, which then became known as BRICS (South Africa 2011). The G-7 countries are the seven wealthiest developed nations and have the largest research and development activities worldwide (King 2004).

This paper first compares the evolution of scientific production of G-7 and BRICS countries between 1995–1997 and 2010–2012 for the fields of Engineering and Technology, Medical Sciences and Earth & Space. The scientific collaboration between BRICS and G-7 countries and its evolution over the period 1995–1997 to 2010–2012 is then analyzed for each major field. Specifically, this paper investigates how this evolution is being influenced by endogenous collaboration (amongst BRICS) and by exogenous collaboration (with G-7 countries). Finally, economic collaboration is explored as a potential factor explaining scientific collaboration using data on high-technology economic exchanges.

Background

Economic and scientific growth

BRICS countries have shown very high economic growth rates in recent years. In 2014, BRICS economies generated more than 20 % of the world's Gross Domestic Product (GDP) (UNCTAD Statistics 2015a), coupled with a significant annual growth rate: 10.0 % for China, 7.3 % for India, 3.6 % for Brazil, 2.8 % for Russia and 2.6 % for South Africa (UNCTAD Statistics 2015b) during the period 2005–2014, while the world's average annual growth rate was at 2.5 %. The BRICS growth in GDP was also accompanied by an increase in their exports. Hanson (2012) noticed a high growth of exports for emerging countries between 1992 and 2008, with an average annual exports growth of 18 % in China and 14 % in India. Furthermore, the share of global exports coming from 15 middle-income countries[1] (in terms of market size) more than doubled during this period, increasing from 21 to 43 %.

Research and development (R&D) is also often linked with economic growth: it typically stimulates R&D spending, and in return R&D spending stimulates economic growth. According to OECD Science, Technology and Industry Outlook (2012), China leads the group of emerging economies, as its share in global R&D spending increased from 7 % in

[1] These countries are: Brazil, South Korea, Mexico, Russia, Argentina, Turkey, Indonesia, Poland, South Africa, Thailand, Egypt, Colombia, Malaysia, Philippines, and Chile.

Table 1 Increase in terms of number of publications for G-7 and BRICS countries, 1995–1997 versus 2010–2012

Country	1995–1997			2010–2012			Increase rate (10–12/95–97)		
	Total papers	International co-authored papers	Single country papers	Total papers	International co-authored papers	Single country papers	Total papers (%)	International co-authored papers (%)	Single country papers (%)
Canada	104,146	29,957	74,189	177,019	83,730	93,289	70	180	26
France	135,200	43,145	92,055	202,597	106,682	95,915	50	147	4
Germany	177,817	54,098	123,719	287,418	145,065	142,353	62	168	15
Italy	83,342	26,326	57,016	167,251	75,102	92,149	101	185	62
Japan	189,908	26,905	163,003	231,426	63,330	168,096	22	135	3
UK	199,982	52,689	147,293	302,631	152,779	149,852	51	190	2
USA	781,578	128,136	653,442	1,093,722	350,461	743,261	40	174	14
G-7	1,671,973	361,256	1,310,717	2,462,064	977,149	1,484,915	47	170	13
Brazil	19,932	7003	12,929	107,547	28,565	78,982	440	308	511
China	44,401	10,505	33,896	490,606	119,467	371,139	1005	1037	995
India	47,109	5720	41,389	139,005	29,950	109,055	195	424	163
Russia	82,627	19,514	63,113	85,232	27,253	57,979	3	40	−8
S. Africa	10,817	2732	8085	27,812	13,891	13,921	157	408	72
BRICS	204,886	45,474	159,412	850,202	219,126	631,076	315	382	296

The total for G7 and BRICS countries includes double counts due to collaboration within G7 or within BRICS. Hence, such numbers have to be considered as country-paper combinations rather than distinct numbers of papers

2004 to 10 % in 2008, and then to 13 % in 2009. OECD data also show that while R&D spending declined in most countries as a result of the economic crisis, Brazil, South Korea, Malaysia, Mexico, Singapore and Argentina continued to increase their spending. Moreover, China, South Korea and other emerging Asian economies are out-innovating the Western world (OECD 2012).

As shown by Leydesdorff and Zhou (2005), these investments lead to a growth in scientific outputs: China, South Korea, Singapore, India, South Africa, Russia and Iran increased significantly their scientific activities. These emerging nations not only increased their share of the world's scientific production but their national science systems also experienced an endogenous growth. The authors thus predict that the center of gravity of the science world will change accordingly. Table 1 confirms these trends, showing that for BRICS countries, single country papers are typically growing as much as papers with foreign colleagues. We could also add that the scientific impact of BRICS papers is likely to increase, as it has been shown that their papers' citation half-lives are increasing at faster rate than that of developed countries' papers (Bouabid and Larivière 2013).

On the technological dimension, a report by BCG (2013) stated that for the 2006–2013 period, the number of patents granted by the United States Patent and Trademark Office (USPTO) to companies based in Rapid Developing Economies (RDEs) increased at a rate more than three times higher than that of companies from other countries. The BCG even predicted that if this growth continued, 25 % of patents issued by the USPTO in 2018 would belong to RDEs.

These data suggest that emerging countries are aiming to build up their national research systems to international quality standards. However, the disciplines in which these countries are active vary greatly. Harzing and Giroud (2014) applied the concept of revealed comparative advantage (RCA) to scientific output to highlight where countries have a scientific advantage (in terms of their areas of specialization). They showed that different countries exhibit very different research profiles: USA, UK, Canada, the Netherlands and Israel have their main RCA in the Social Sciences while China, Singapore, Taiwan and South Korea have a very strong RCA in Engineering and Technology with comparative disadvantages in all other disciplines with the exception of Physical Sciences. India is characterized by a modest RCA in Physical Sciences but demonstrated a rather strong comparative disadvantage in the Social Sciences. Russia also has a strong RCA in Physical Sciences. South Africa has a RCA in Social Sciences and Environmental Sciences.

Yang et al. (2012) found that there is a certain relationship between countries' areas of specialization and their level of science and technology (S&T) activities. While the disciplinary structure of all G-7 countries is similar to that of other high S&T countries, BRICS countries' research systems share fewer common characteristics. The authors also showed that, from 1991 to 2009, the disciplinary structure of BRICS countries has evolved from being quite unbalanced—with the focus on only a few disciplines—to a much more balanced blend of disciplines similar to what is seen in G-7 countries. They concluded that, for BRICS countries, the reconfiguration of the disciplinary structure moves in parallel with a strong development of S&T activities. However, this study did not address the question of science collaboration between BRICS and G-7 countries and if collaboration plays any role in developing their domestic scientific output in terms of disciplinary structure.

The increase of emerging countries' scientific output is to some extent driven by human resources mobility and international collaboration. Mobility refers to the training of BRICS' highly qualified scientists in developed countries, mainly in the USA, Japan, Canada and Western Europe. According to the Institute of International Education (2013), for the 2012–2013 period the USA hosted more than 34,000 Chinese scholars, 11,000 Indians, 3200 Brazilians and 1100 Russians. The return of these researchers to their homelands constitutes a strong transfer of science and technology to their respective countries, in addition to the fact that they typically maintain collaborative ties with their host institutions.

A second driver for BRICS' scientific productivity is the international collaboration between researchers from BRICS countries and their peers worldwide. Indeed, many authors have shown a positive relation between research productivity and scientific collaboration. Lee and Bozeman (2005), Larivière et al. (2006), He et al. (2009), Abramo et al. (2011) and Finlay et al. (2012) have all shown that collaboration is related with research output and scientific impact. Similarly, Defazio et al. (2009) found that while funding increased researcher productivity by approximately 14 %, collaboration increased it by almost 70 %. The positive effect of collaboration on the scientific impact of papers has also been shown using citations analysis (de Beaver 2004; Katz and Hicks 1997; Larivière et al. 2015; Levitt and Thelwall 2010; Rigby 2009). Finally, Sun et al. (2013) found that scientific disciplines emerge from the splitting and merging of social communities in a collaboration network, which supports the theory that scientific collaboration shapes the dynamics of science.

Data and methods

Data are drawn from Thomson Reuters' Web of Science database (WoS). Three scientific fields, based on the NSF field and subfield classification, were considered in the present analysis: Engineering & Technology, Medical Sciences (which includes Biomedical Research, Clinical Medicine and Health) and Earth & Space. Two periods are considered, 1995–1997 and 2010–2012. The first period was fixed before the creation of the BRICS alliance and the second one a decade and a half after, to measure the effect, if any, of this alliance on the scientific collaboration between these countries. Scientific collaboration between two countries is measured by the number of co-authored papers from these two countries and full counting is used. Before mapping scientific collaborations, matrixes are normalized using Jaccard Index (Jaccard 1901) as done by Hamers et al. (1989), Klavans and Boyack (2006) and Leydesdorff (2008).

Consider the matrix $[X] = X_{ij}$ where $1 \le i,j \le n$ represents the gross matrix of the number of co-authored papers between the countries i and j. The normalized matrix $[J] = J_{ij}$ using the Jaccard index is written as:

$$J_{ij} = \frac{X_{ij}}{X_{im} + X_{mj} - X_{ij}}$$

where

$$X_{im} = \sum_{j=1}^{n} X_{ij} \text{ and } X_{mj} = \sum_{i=1}^{n} X_{ij}$$

The last step in mapping is generating the science maps which can be done using one of the available and specifically conceived tools for science mapping. All the maps presented in this paper are produced using Gephi software after normalizing the collaboration matrix with Jaccard index as presented above. The respective scientific size of each country in a given field is the number of papers published by this country in this field.

Results and discussion

Evolution of countries' scientific production

Table 2 presents the number of papers produced by G-7 and BRICS countries between 1995–1997 and 2010–2012 in major scientific fields. Unsurprisingly, the USA is still at the center of the world's scientific production. No significant change has occurred from the 1995–1997 to 2010–2012, except in the field of Engineering and Technology, where it has lost its leading position to China. Moreover, China significantly increased its scientific production in all considered fields between 1995–1997 and 2010–2012. Unsurprisingly, Russia has, by far, the lowest growth rate among the BRICS countries in all scientific fields, as it is still recovering from the fall of the USSR. Let us recall that for most of the second half of the twentieth century, the USSR was the second most active scientific superpower, surpassed only by the USA (Graham 1993).

Evolution of scientific collaboration

China's scientific collaboration with G-7 countries grew substantially between 1995–1997 and 2010–2012 (Figs. 1, 2, 3 and "Appendix 1" for the raw matrixes of collaboration). Figure 1 shows that China's scientific output exceeded that of the USA in Engineering and Technology in 2010–2012. In this field, India and Brazil have also increased their scientific output and intensified their collaboration with almost all G-7 countries. Two major factors may contribute to this growth as well as the typical pattern of scientific development it follows (Basalla 1967): tertiary students' mobility and high technology activities of BRICS countries. Indeed, the OECD report (2013) on international student mobility stated that the largest numbers of international students in 2011 were from China (723,000), India (223,000), Korea (139,000) and Russia (71,000), and that Brazil topped the countries of Central and South America. These students play a key role in the intensification of research collaboration when back in their country of origin, maintaining research ties with colleagues from host countries. This report also shows that five of the six most attractive countries for foreign tertiary students are G-7 countries: USA, UK, Germany, France and Canada. Regarding the second major factor, high-technology exports of BRICS economies to G-7 economies have significantly increased (UNCTAD Statistics 2014), which might be both a cause and a consequence of more research activities in these domains. For example, 'Electronics (excluding parts and components), SITC 751 + 752 + 761 + 762 + 763)' exports from BRICS[2] to G-7 economies have grown approximately 624 % from 1995 to 2012, reaching 123.6 billon US$ in 2012 (despite a decrease in Brazil's exports and South Africa's small increase of 4.2 %). Similarly, BRICS exports of 'Machinery and transport equipment, SITC 7' also grew 542 % during the same period, reaching more than 423 billion US$ in 2012.

Figure 2 provides the collaboration network of BRICS and G-7 countries in Medical Sciences. In fact, Medical Sciences is the only field where no noticeable change can be observed in BRICS and G-7 collaboration patterns, except for China, which is now much

[2] Statistic for China refers to China PR, Hong Kong, Macao and Taiwan.

Table 2 Number of papers of G-7 and BRICS countries, by scientific area, 1995–1997 and 2010–2012

Country	Engineering and technology			Medical sciences			Earth and space		
	95–97	10–12	Increase rate (%)	95–97	10–12	Increase rate (%)	95–97	10–12	Increase rate (%)
Canada	10,981	20,382	86	42,912	78,233	82	7668	13,459	76
France	11,456	24,350	113	58,561	77,106	32	8173	17,678	116
Germany	17,022	28,138	65	74,815	121,577	63	8889	21,956	147
Japan	25,884	30,351	17	81,670	99,666	22	4629	11,198	142
UK	18,908	26,489	40	94,534	136,463	44	11,127	21,858	96
USA	71,934	96,748	34	372,557	530,395	42	40,943	65,488	60
G-7	163,598	244,920	50	765,248	1,120,537	46	85,896	164,981	92
Brazil	1438	8121	465	7,692	51,195	566	1052	4138	293
Russia	9314	9878	6	15,260	12,163	-20	5458	8981	65
India	7758	24,073	210	12,256	43,472	255	2801	8893	217
China	7877	105,160	1235	7185	128,427	1687	1735	28,544	1545
S. Africa	818	2166	165	3888	9257	138	1065	2254	112
BRICS	27,205	149,398	449	46,281	244,514	428	12,111	52,810	336

The total for G7 and BRICS countries includes double counts due to collaboration within G7 or within BRICS. Hence, such numbers have to be considered as country-paper combinations rather than distinct numbers of papers

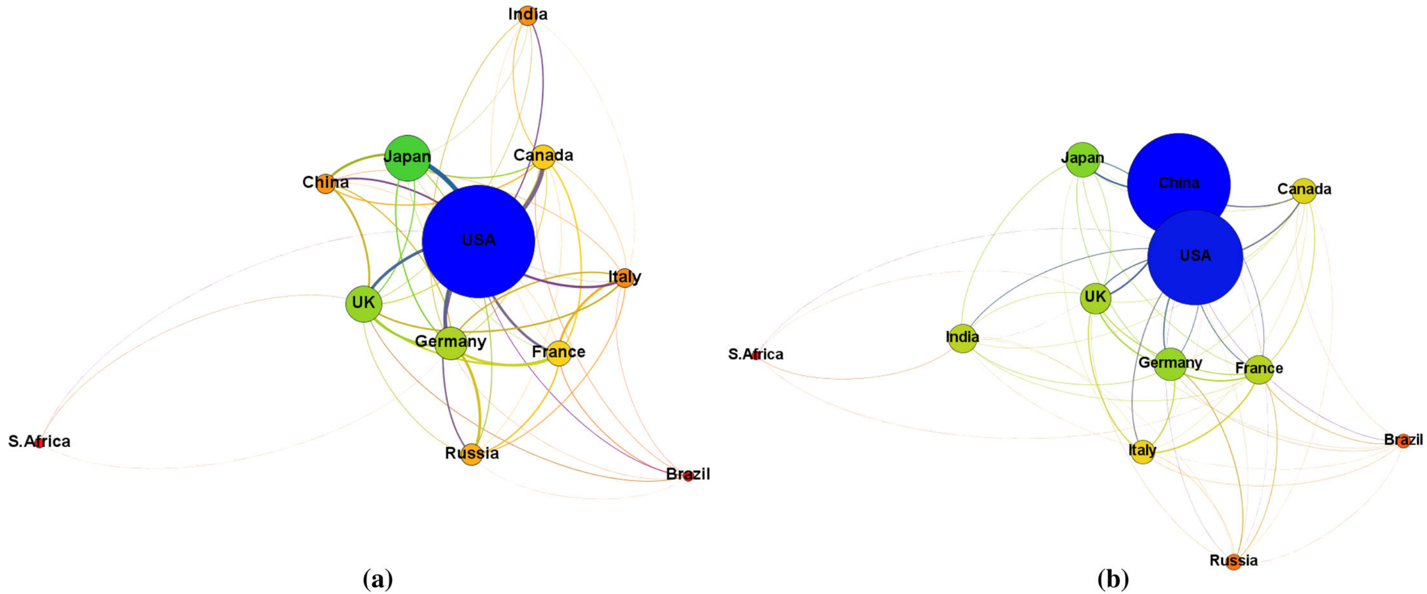

Fig. 1 Scientific collaboration of G-7 and BRICS countries in the field of Engineering and Technology. The size of the circle refers to the number of articles, thickness of the link refers to the intensity of the co-publications and the distance between two entities refers to their respective proximity in the cluster. **a** Period 1995–1997. **b** Period 2010–2012

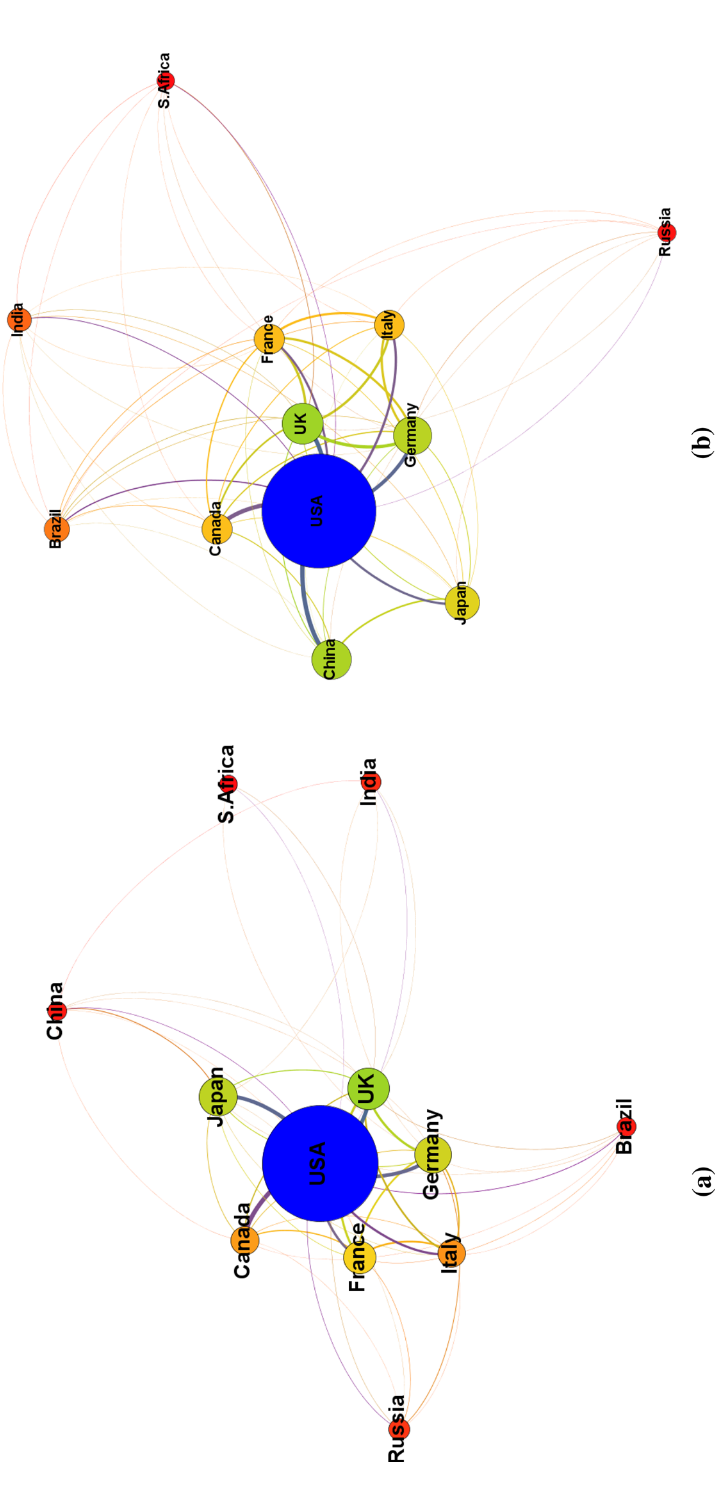

Fig. 2 Scientific collaboration of G-7 and BRICS countries in the field of Medical Sciences. The size of the circle refers to the number of articles, thickness of the link refers to the intensity of the co-publications and the distance between two entities refers to their respective proximity in the cluster. **a** Period 1995–1997. **b** Period 2010–2012

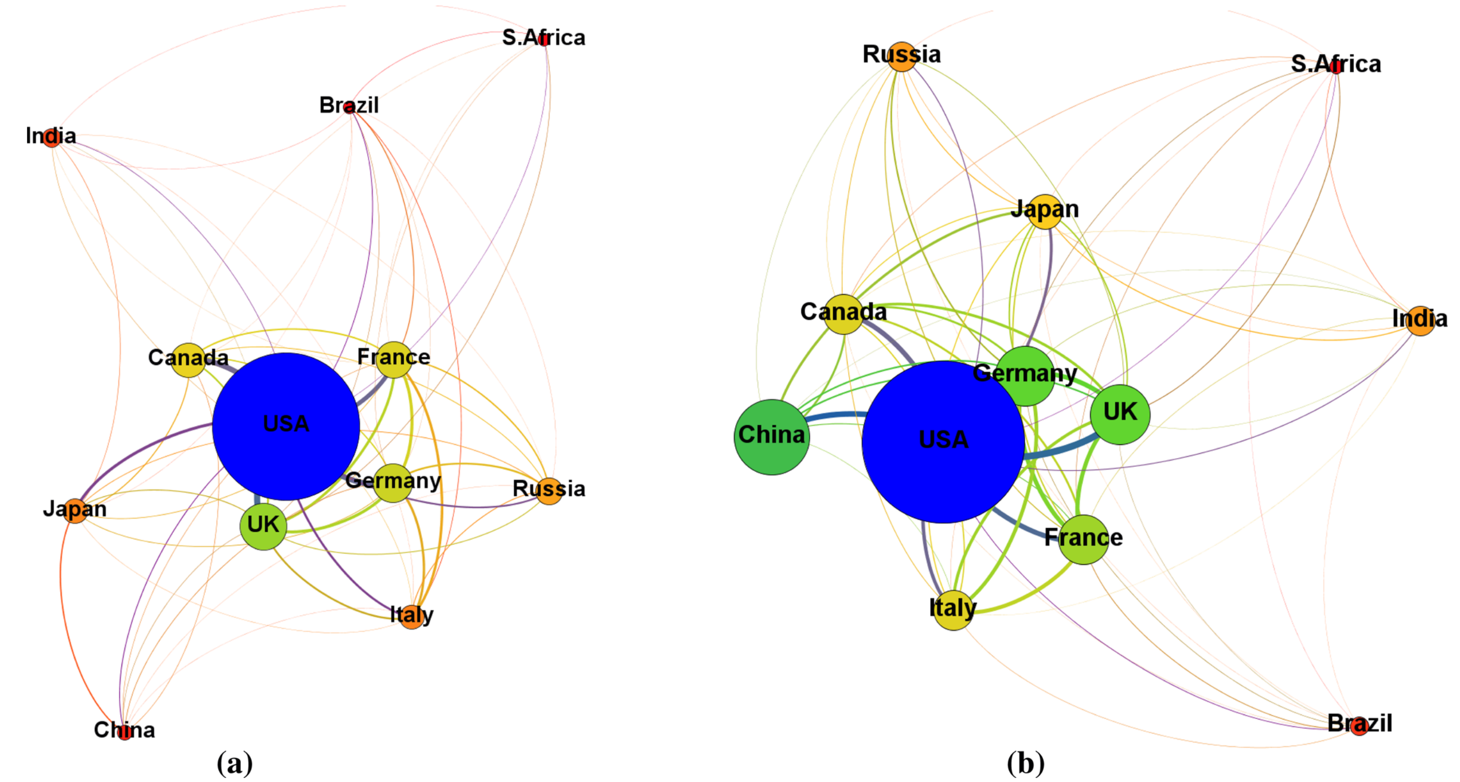

Fig. 3 Scientific collaboration of G-7 and BRICS countries in the field of Earth and Space. The size of the circle refers to the number of articles, thickness of the link refers to the intensity of the co-publications and the distance between two entities refers to their respective proximity in the cluster. **a** Period 1995–1997. **b** Period 2010–2012

closer to the G-7 cluster. The G-7 group has remained the core of the network with intensive scientific collaboration among its constituents. Brazil, Russia, India and South Africa remain at the cluster's periphery even if their scientific production has significantly increased between the two periods. While no increase has occurred in the BRICS intra-closeness and intra-collaboration, the growth rate of the Medical Sciences output for each BRICS country is largely exceeding the rate observed for G-7 countries (Table 2). As health appeared to be an important issue at the 3rd BRICS Summit in 2011 (Harmer and Fleck 2014), intensification of BRICS' Medical Sciences production and intra-BRICS collaboration could be expected. Since 2011, BRICS has held annual meetings discussing specific health issues, which have been found to be different than those of the Organization of Economic Co-operation and Development (OECD) countries (Harmer and Fleck 2014).

Earth and Space is the second field in which China demonstrates a strong progression, with a research output that is greater than that of all other G-7 countries except the USA ("Appendix 1" for the raw matrix). In 2013, China successfully landed the unmanned Chang'e-3 spacecraft on the moon, becoming the first country to carry out a lunar touchdown in almost four decades, and the third country in the world—after the USA and Russia—to reach Earth's satellite. China's first self-built rocket was launched in 1990 carrying a satellite into orbit (Lakdawalla 2014) and in 2003, China's first astronaut was successfully sent into Earth's orbit (Liao 2005). These clear advances in Earth and Space can also be related to the growing Chinese scientific production and intensifying collaboration with G-7 countries in Engineering and Technology (Fig. 1).

Along these lines, India's first astronaut flew in 1984 as part of the Soviet Soyuz mission. In 2008, India successfully launched its first rocket into moon orbit, the Chandrayaan-1, in search of water evidence (Goswami and Annadurai 2009). Despite that space experience, India does not show the same level of collaboration with G-7 countries in Earth and Space (Fig. 3). Moreover, India's progress in the field of Engineering and Technology, both in terms of production and collaboration, is relatively less important than that of China (Fig. 1).

As South Africa was the last country to join the BRIC alliance in 2011, it seems that its "scientific integration" is still to come. Indeed, as shown in Figs. 1, 2 and 3, it is the farthest from either the G-7 or other BRICS countries in all scientific fields studied. Even if the number of papers produced by South Africa has substantially increased between 1995–1997 and 2010–2012 (Table 2), the country is still at the periphery of the BRICS cluster, and far away from the G-7 cluster. Its main partners are the UK and USA, which suggests that its scientific output growth (408 %, see Table 2) is rather exogenous than endogenous, and due to international collaborations.

Figures 1, 2, 3 show that the scientific collaboration amongst BRICS countries did not grow as fast as that between BRICS and G-7. In contrast to G-7 countries, where proximity in terms of scientific collaboration has proven to be enduring, the increase of BRICS' scientific production, when observed, seems to be more individual and endogenous than resulting from any alliance or collective enterprise. According to Chan and Daim (2012), when exploring the role of technology foresight activities with regards to innovation in BRICS countries, one has to consider differences in their aspirations concerning their future role in the global economy, political will, availability of economic resources, technological positions, and social conditions, which may help explain the more competitive than collaborative nature of the scientific relationship between China and India. "Cooperation in S&T" was one of the five priorities of the G-7 as early as 1985 and may explain the dense scientific cluster of G-7 countries seen in Figs. 1, 2, 3 and the difference between the G-7 group and the BRICS group. Indeed, BRICS are a quite heterogeneous group, while all G-7 countries except Japan are of European heritage, with historical ties related to language and culture. Such ties do not exist between Russia and Brazil or China and India. Moreover, four of the G-7 countries—Germany, France, Italy and UK—are members of the European Union, which has fostered, through structured science and technology research programs, scientific cooperation over the last few decades. Such programs of scientific cooperation do not yet exist at the level of BRICS countries despite an explicit resolution made during the first BRIC Summit in 2009 (resolution no 11 of the Joint Statement[3]), reaffirmed in the second Summit in 2010 (resolution no 29 of the Joint Statement[4]) and even in later summits.

On the whole, these results suggest that the BRICS alliance is much more based on political and economic relations than scientific ones. The scientific intra-collaboration intensity (links) and proximity (distances) between these countries are weak and do not seem to evolve in a positive direction. This seems to confirm the results of Finardi (2014), who showed that some relatively strong collaboration ties exist but these intra-ties were not necessarily the strongest the countries experienced. Geographical distance may explain in part these weak collaboration links (Acosta et al. 2011; Hoekman et al. 2010; Scherngell and Yuanjia 2011). Indeed, the mean geographical distance of the BRICS group is 9383 km (with a standard deviation of 4867 km) which is almost twice the mean distance of the G-7 group: 5708 km (with a standard deviation of 3503 km).

Scientific Collaboration and High-technology Exchanges

In order to obtain a broader understanding of the scientific collaboration between countries, numerous factors have to be taken into account. Harzing and Giroud (2014) recently proposed a model detailing factors that may explain research profile and scientific competitiveness of a country. These factors include the *Demand conditions* (e.g. academic population, public and private sectors); the *Factor conditions* (e.g. human resources, physical resources, knowledge resources and capital resources); the *Strategy, structure and rivalry* (e.g. university goals and strategy, competition); the *Related and supporting industries* (e.g. non-higher education research institutions and the IT industry); the *Government* (e.g. education and R&D funding policy) and a part of *Chance* whose effect cannot be easily predicted. Others have found a positive correlation between economic development and scientific collaboration, within Europe (Acosta et al. 2011) and within China (Scherngell and Yuanjia 2011). However, the relationship between scientific cooperation and high-technology economic exchanges has never been explored, despite the commonly made assumption that we globally are in a knowledge and technology-based economy.

We explore here the relation between scientific collaboration and high-technology exports between BRICS and G-7 countries. As shown in Fig. 4, high-technology exports[5] of most BRICS countries have increased, especially exports made to G-7 countries (except for

[3] Resolution no 11 (2009 Summit): *We reaffirm to advance cooperation among our countries in science and education with the aim, inter alia, to engage in fundamental research and development of advanced technologies.*

Source: BRICS Information Center, University of Toronto (www.brics.utoronto.ca).

[4] Resolution no 29 (2010 Summit): *We reaffirm our commitment to advance cooperation among BRIC countries in science, culture and sports.*

Source: BRICS Information Center, University of Toronto (www.brics.utoronto.ca).

[5] Includes 'Electronics (excluding parts and components) (SITC 751 + 752 + 761 + 762 + 763)', 'Parts and components for electrical and electronic goods (SITC 759 + 764 + 776)', 'Machinery and transport equipment (SITC 7)', 'Medicinal and pharmaceutical products' (UNCTAD Statistics 2014).

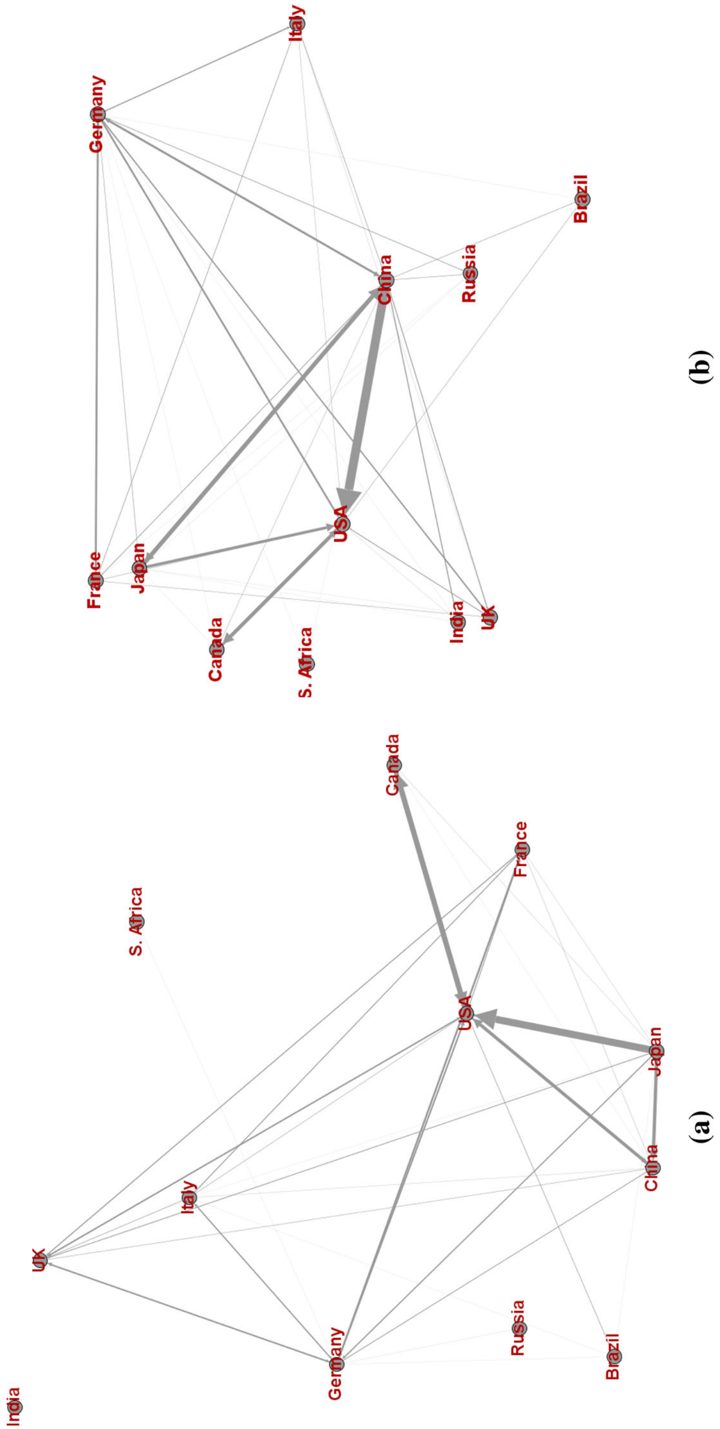

Fig. 4 High-technology import/export flows between G-7 and BRICS countries. The thickness of the link refers to the intensity of the exports and the distance between two entities refers to their respective proximity in the cluster. **a** Period 1,995–1,997. **b** Period 2010–2012

Table 3 Modularity value and clustering index for BRICS and G-7 cluster

Period	Modularity[a]	Clustering coefficient[b]
1995–1997	0.229	0.586
2010–2012	0.243	0.760

[a] Using the Louvain Method for community detection which allows for detection and study of communities having closer 'distance' within the cluster. The algorithm generates 'modularity classes' which may be colored differently for network visualization and analysis (Blondel et al. 2008)

[b] The clustering coefficient is the weighted value for every node in the cluster. It captures more precisely the effective level of cohesiveness and affinity due to the interaction strength between nodes (Latapy 2008)

Brazil) from the 1995–1997 period to 2010–2012. The proximity (closeness) of BRICS countries, led by China, also increased though along different paths. The economic competitiveness of BRICS countries among themselves is made visible by the very weak exports flows seen between BRICS countries in Fig. 4. On the contrary, the export flows of each BRICS country toward the G-7 group has intensified globally from 1995–1997 to 2010–2012. China has become a pivotal actor in the high-technology flows of the BRICS and G-7 network for the 2010–2012 period, a position that was held until then by the USA. On the opposite end, France's position in the network of exchanges has decreased, both in terms of flow intensity and proximity. The total value of exports made by the USA to BRICS and G-7 countries increased by 37.1 % between the 1995–1997 and 2010–2012 period, the exports made by the UK increased about the same amount (37.6 % between 1995–1997 and 2010–2012) and Japan increased its exports of 41 %, again for the same period. The exports flows of BRICS countries show a quite different picture: India's exports to BRICS and G-7 countries increased 1066 % between 1995–1997 and 2010–2012, while the exports made by China increased 538, 167.2 % for exports made by South Africa, 151.1 % for exports made by Russia and 131.8 % for exports made by Brazil (see "Appendix 2").

The increasing proximity of BRICS countries to the G-7 cluster is explained by the improvement of the whole BRICS and G-7 cluster proximity. Indeed, Table 3 shows the increase in modularity value passing from 0.229 in 1995–1997 period to 0.243 in 2010–2012 period. Simultaneously, the clustering index moved from 0.586 to 0.760 during the same period (Table 3).

Conclusion

Using Web of Science's scientific collaboration data and maps, this paper demonstrates that BRICS countries' increase in scientific production is to a large extent enhanced by BRICS' international collaboration, mainly with G-7 countries. For the 1995–1997 to 2010–2012 period, the USA remains at the center of the world's scientific production in almost all scientific fields while China is the fastest growing country both in terms of its scientific production and its collaboration proximity with G-7 countries. Maps of BRICS and G-7 collaboration clusters, based on the intensity of collaborations as well as on their proximity, provide evidence that Brazil, Russia, India and South Africa still remain at the periphery of the cluster even if their scientific output has significantly increased between 1995–1997 and 2010–2012. Furthermore, scientific collaboration amongst BRICS countries has not grown as fast as that between BRICS and G-7, suggesting that BRICS countries are individually collaborating with the G-7 countries that are still at the core of the scientific collaboration network with intensive intra-collaboration activities

While high-technology exports made by most BRICS countries to G-7 countries have increased between 1995–1997 and 2010–2012, the intra-BRICS high-technology exchanges as well as the intra-BRICS scientific collaboration have remained very weak, which might be the result of several factors, namely: the competitiveness of BRICS countries among themselves, geographical distance (as the mean geographical distance of the BRICS group is almost twice the mean distance of the G-7 group), the lower purchasing power of some of these countries, and the lack of political will to fulfill the science cooperation agenda explicitly set during their first summit in 2009.

Our findings also suggest a relationship between high-technology economic activities of BRICS countries, the growth in their scientific production and their exogenous collaboration in intensive and technologically-related scientific activities. As BRICS countries increase their technological output and exchanges with G-7 countries, scientific relationships between both groups of countries also increase which, in turn, positively affects the research infrastructure of BRICS countries and certainly leads to more scientific output. More research is necessary, however, to assess the extent of this relationship as well as the effects of collaborating with specific countries.

Appendix 1

Engineering and Technology co-publications for the period 1995–1997

	Brazil	Canada	China	France	Germany	India	Italy	Japan	Russia	S. Africa	UK	USA
Brazil		49	11	71	45	7	30	16	18	0	72	165
Canada			151	205	143	78	67	188	51	11	153	1031
China				57	166	3	59	270	10	2	231	461
France					400	38	267	82	161	6	264	678
Germany						93	222	239	336	21	377	1018
India							22	43	8	1	62	309
Italy								59	83	3	217	580
Japan									114	2	175	1123
Russia										9	88	386
S. Africa											35	46
UK												777
USA												

Engineering and Technology co-publications for the period 2010–2012

	Brazil	Canada	China	France	Germany	India	Italy	Japan	Russia	S. Africa	UK	USA
Brazil		142	110	355	252	79	166	52	66	13	204	612
Canada			1863	651	402	234	245	316	68	30	445	2473
China				1059	1216	215	288	2369	189	62	2848	8527
France					1432	311	1142	454	407	92	1009	1808
Germany						411	949	538	587	65	1389	2455
India							173	313	77	98	344	1296
Italy								221	189	25	943	1679
Japan									148	15	501	1654
Russia										12	229	486
S. Africa											109	161
UK												2178
USA												

Medical Sciences co-publications for the period 1995–1997

	Brazil	Canada	China	France	Germany	India	Italy	Japan	Russia	S. Africa	UK	USA
Brazil		165	21	241	188	17	80	98	27	11	345	1118
Canada			102	1182	777	54	433	626	99	57	1372	7570
China				134	132	22	47	413	25	4	206	824
France					1871	85	1521	544	325	80	2480	4574
Germany						122	1314	845	542	114	2845	6792
India							42	83	16	5	216	554
Italy								309	145	44	1868	4105
Japan									119	35	1108	6425
Russia										6	336	905
S. Africa											258	341
UK												7611
USA												

Medical Sciences co-publications for the period 2010–2012

	Brazil	Canada	China	France	Germany	India	Italy	Japan	Russia	S. Africa	UK	USA
Brazil		1178	328	1169	1216	250	1059	387	116	207	1664	5821
Canada			2553	3667	4032	608	2423	1419	266	460	6173	20,856
China				1231	2204	466	789	3247	273	168	3280	20,640
France					6937	529	5561	1458	507	465	8152	11,810
Germany						696	6722	2166	879	492	11,779	19,770
India							393	534	82	187	1234	3656
Italy								1071	394	290	8011	12,655
Japan									222	133	2590	10,986
Russia										63	617	1600
S. Africa											1616	2408
UK												23,715
USA												

Earth and Space co-publications for the period 1995–1997

	Brazil	Canada	China	France	Germany	India	Italy	Japan	Russia	S. Africa	UK	USA
Brazil		41	9	136	63	14	67	27	19	17	88	240
Canada			69	309	289	24	81	152	115	34	368	1557
China				82	114	7	23	99	27	7	94	276
France					663	49	417	130	230	33	592	1412
Germany						81	433	149	319	68	703	1796
India							30	42	20	9	68	198
Italy								51	104	18	353	696
Japan									79	14	182	842
Russia										11	174	546
S. Africa											93	154
UK												1983
USA												

Earth and Space co-publications for the period 2010–2012

	Brazil	Canada	China	France	Germany	India	Italy	Japan	Russia	S. Africa	UK	USA
Brazil		140	76	402	377	50	202	83	47	49	300	756
Canada			1010	1359	1486	162	736	482	205	202	1874	4425
China				666	1190	146	341	1001	183	71	1188	4768
France					3258	290	2303	840	541	311	3104	5035
Germany						382	2463	1022	904	389	3757	6454
India							152	271	100	79	287	889
Italy								546	339	170	2110	3364
Japan									284	116	989	2596
Russia										61	487	966
S. Africa											497	561
UK												6938
USA												

Appendix 2

Total high-technology exports[a] between BRICS and G-7 countries during the period 1995–1997

Economy partner	Brazil	Canada	China	France	Germany	India
Brazil		1,108,274.57	5,535,033.68	2,300,504.26	9,493,056.27	57,877.243
Canada	221,206.198		8,317,911.49	3,141,493.76	5,864,859.7	84,703.051
China	515,930.426	4,768,989.53		17,403,664	30,159,106.2	494,534.607
France	593,627.933	1,656,268.87	11,123,586.7		96,591,463.8	140,093.125
Germany	1,338,511.35	2,702,556.37	32,143,451.5	73,327,852.4		614,833.998
India	58,460.466	219,377.926	3,158,104.7	1,746,650.03	5,253,224.26	
Italy	1,022,789.75	601,976.218	6,795,436.96	33,278,495.6	60,869,105.7	245,342.467
Japan	235,894.191	1,442,138	67,426,234.4	4,190,650.98	25,910,246.7	118,273.571
Russia	32,097.585	343,591.131	1,590,619.85	2985800.86	12,283,325.4	408,248.526
S. Africa	388,552.332	201,510.789	3,833,399.53	1,663,339.61	8,669,576.65	145,862.55
UK	562,983.063	3,561,251.16	22,280,976.2	44,363,375	79,249,427.4	887,791.014
USA	9,281,469.95	241,385,697	172,785,615	31,254,443.7	84,043,622.3	1,880,985.5
Economy partner	**Italy**	**Japan**	**Russia**	**S. Africa**	**UK**	**USA**
Brazil	6,585,713.91	7,008,407.01	6,609.451	89,165.132	2,165,389.08	32,114,426.9
Canada	2,581,526.02	16,645,337.5	33,135.618	104,652.077	4,948,961.7	278,958,834
China	12,541,724.6	174,667,606	2,035,615.23	504,784.037	13,584,303.6	96,642,591.7
France	41,700,050.3	16,985,807.6	96,282.39	498,361.189	40,529,069.8	35,735,812.6
Germany	47,274,032	63,204,579.8	979,354.577	2,747,261.39	60,817,804.2	54,521,915.1
India	1,965,155.01	4,374,663.2	1,054,811.26	289,602.752	2,758,528.81	6,165,868.99
Italy		9,626,026.84	109,004.824	261,658.747	22,843,434.8	16,124,896.6
Japan	3,876,925.63		151,232.478	532,500.109	13,444,269.3	115,364,810

Economy partner	Italy	Japan	Russia	S. Africa	UK	USA
Russia	4,250,135.02	3,125,188.11		24,697.987	3,112,746.8	4,075,608.28
S. Africa	2,399,015.06	5,215,853.06	4,730.313		6,052,733.56	5,521,300.57
UK	23,389,342.1	43,185,341.6	153,357.265	1,584,003.64		76,683,916.1
USA	22,076,804.4	374,359,641	320,235.981	1,709,587.02	57,684,256.6	

[a] Which includes: 'Electronics (excluding parts and components) (SITC 751 + 752 + 761 + 762 + 763)', 'Parts and components for electrical and electronic goods (SITC 759 + 764 + 776)', 'Machinery and transport equipment (SITC 7)', 'Medicinal and pharmaceutical products'

Total high-technology exports[a] between BRICS and G-7 countries during the period 2010–2012

Economy partner	Brazil	Canada	China	France	Germany	India
Brazil		2,537,253.61	70,666,480.7	9,810,857.78	26,691,010.4	2,087,242.51
Canada	991,945.726		53,453,342.7	4,737,524.96	21,656,047.8	901,704.232
China	3,834,264.87	7,942,057.86		50,376,341.3	217,196,480	5,427,026.47
France	1,522,463.88	4,522,375.95	77,749,618.2		226,694,799	2,906,982.87
Germany	5,280,281.74	4,837,382.23	213,177,059	151,525,172		6,008,122.76
India	763,614.794	1,478,318.71	123,846,794	7,370,333.88	24,517,194.7	
Italy	1,665,948.74	1,474,353.96	70,291,088	44,979,299.7	124,653,569	3,443,127.97
Japan	559,158.976	2,258,458.04	355,441,941	10,144,637.5	39,220,385.8	1,300,712.65
Russia	330,427.623	2,295,825.57	67,461,182.6	18,629,134.1	85,292,540.9	3,299,508.86
S. Africa	1,980,408.99	843,383.67	23,301,796.7	5,132,571.18	23,208,932.9	5,415,742.47
UK	1,616,130.41	6,583,497.42	101,301,619	44,510,169.7	155,854,807	6,045,528.13
USA	14,485,197.1	300,398,111	979,671,914	50,710,189.4	214,285,973	22,380,937.9
Economy partner	Italy	Japan	Russia	S. Africa	UK	USA
Brazil	12,426,676.3	13,317,077	81,423.658	319,920.861	5,886,598.78	61,242,834.5
Canada	3,849,842.48	24,466,136.8	48,197.372	504,593.225	9,620,967.11	421,686,868
China	27,123,295.6	484,992,004	3,507,670.3	809,485.138	43,941,631.1	214,388,418
France	65,350,976	16,147,164.2	341,392.201	1,251,528.31	36,676,909.8	31,109,824.6
Germany	74,013,103.1	52,969,171	1,772,505.03	7,137,069.28	68,851,353.1	74,715,223
India	8,538,856.34	17,761,377	4,434,286.8	317,476.11	6,256,034.37	18,408,389
Italy		10,540,336.2	174,977.18	240,337.141	24,604,641.4	19,444,928.2
Japan	7,181,549.28		799,120.816	1,427,257.51	11,222,912.5	65,888,548.5
Russia	15,469,563.2	28,461,925.2		333,430.236	14,532,930	13,023,144.9
S. Africa	3,438,102.96	10,234,082.6	101,001.027		6,651,042.14	10,384,149.1

Economy partner	Italy	Japan	Russia	S. Africa	UK	USA
UK	29,828,737.6	28,851,672.4	276,240.857	2,003,242.72		59,348,056.1
USA	43,565,489.1	324,882,146	878,554.417	7,960,331.9	85,360,632.4	

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