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2019

Is there convergence in international research collaboration? An exploration at the country level in the basic and applied science fields[1]

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Abstract

This paper examines the patterns of convergence in international scientific collaboration across a set of developed and developing countries from 1997 through 2012. The empirical analysis was carried out in a novel way applying the methodology developed by Phillips and Sul (2007, 2009) to international co-publication data from a US National Science Foundation dataset (NSF, 2014). First, the convergence analysis across countries is carried out for all research fields combined and, secondly, for the basic and applied science fields separately. The results suggest that there has not been an overall convergence in international scientific collaboration patterns during the analyzed period. In contrast, there is evidence of four scientific convergence clubs and three divergent countries in the aggregate of all research fields. However, our results seem to indicate that there is a tendency toward a gradual convergence among the more scientifically developed countries. The results also show the existence of international research collaboration convergence clubs for the fields of basic science research and applied science with five and four convergence clubs, respectively.

Keywords: international research collaboration; scientific convergence clubs; log t test; research fields

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[1] Final version available at https://doi.org/10.1007/s11192-019-03133-9
Barrios, C., Flores, E., Martínez, M.Á. et al. Is there convergence in international research collaboration? An exploration at the country level in the basic and applied science fields. Scientometrics 120, 631–659 (2019). https://doi.org/10.1007/s11192-019-03133-9

1. Introduction

Knowledge-based societies consider scientific knowledge and innovation as engines of economic growth, boosting their production and diffusion (European Commission 2010). Increasingly, scientific knowledge is being generated as a result of scientific collaboration among researchers in teams who generally come from different disciplines (Bozeman et al. 2013; Cummings and Kiesler 2014; Coccia and Bozeman 2016).

Several papers have shown that scientific collaboration leads to an increase in scientific productivity and a higher impact of publications (Lee and Bozeman 2005; Bozeman et al. 2013; Uddin et al. 2013). Scientific collaboration makes the production of knowledge more efficient and shortens the time for obtaining research results due to a division of labour (Coccia and Bozeman 2016). Many other reasons related to economic and socio-cognitive factors such as access to expertise and equipment, pooling resources, obtaining visibility, improve access to funds, and cross-fertilization of disciplines, among others (Bozeman and Corley 2004) have been suggested in the literature as drivers of scientific collaboration. The growing interest in this topic is reflected by the ample literature that has focused on research collaboration patterns at the individual level (Bozeman and Gaughan 2011; Rostan and Ceravolo 2015), institutional level (Lee et al. 2011; Thijs and Glänzel 2010), and regional/country level (Hoekman et al. 2010; Finardi 2015).

In addition, collaboration in scientific research is increasingly global, crossing national boundaries (Carayannis and Laget 2004). The research collaboration literature shows a rapid increase in international scientific collaboration worldwide in recent decades (Abt 2007; Mattsson et al. 2008), growing faster (Leydesdorff and Wagner 2008), and having a greater impact than domestic collaboration (Frenken et al. 2009; Sooryamoorthy 2009; Adams 2013).

This paper focuses on the dynamics of growth in international scientific collaboration activity at the country level, exploring the pattern of convergence over time, a question for which there has been little research. It is particularly interested in learning if there has been global convergence or divergence or if different clusters have appeared in international research collaboration activity across countries over time. In addition, it examines whether there have been differences in the patterns of convergence for basic and applied science fields across countries.

The paper analyses the convergence in international research collaboration activity among a set of 40 developed and developing countries during 1997-2012. To carry out our empirical analysis, we used a methodology developed by Phillips and Sul (2007, 2009) that allows us to discern whether there has been a process of overall convergence among the countries in the sample or if, on the contrary, the countries have converged into or diverged from clubs. First, the convergence analysis across countries is carried out jointly for all research fields combined and, secondly, for the basic and applied scientific fields separately. In the paper, international scientific collaboration is measured by the number of papers co-authored by researchers from different nations (in per capita terms). The co-authorship data approached by statistical analysis or by co-authorship networks (Uddin et al. 2013) is a good proxy for analysing collaboration (Adams 2012) and an indicator widely used in the literature on scientific collaboration (Abt 2007; Choi 2012; Coccia and Bozeman 2016).

The paper contributes to the existing literature in several ways. The main contribution is to apply the Phillips and Sul methodology (2007, 2009) to international research collaboration data. The methodology has previously been applied to socioeconomic variables, but to our knowledge, it has not been utilised for international collaboration activity data. Second, it brings relevant evidence regarding the convergence process in international research collaboration across countries for a large sample of developed and developing countries around the world about which evidence is scarce. Finally, it provides new evidence on the patterns of convergence across countries in international collaboration for basic science and applied science separately.

The remainder of this paper is organized as follows: Section 2 reviews the literature about international research collaboration. Section 3 describes the data and the methodology applied to analyse the convergence patterns in international research collaboration. Section 4 is split in two parts. Section 4.1 provides the results of a descriptive analysis of international research collaboration for the countries in our sample. Section 4.2 reports the results of the empirical analysis with the identification of scientific convergence clubs. Main conclusions are drawn in Section 5.

2. Theoretical background

The development of modern science has motivated a growing interest in researching scientific activities (Mao et al. 2017). The mobility of researchers and the need to solve the complex problems of present-day societies are some causes of the increase in scientific collaboration (Wagner et al. 2017). International scientific collaboration has increased considerably in most countries and for all sciences in the last decades (Wagner et al. 2001). The growth path of international scientific collaboration is relevant because it is a means for international knowledge diffusion as well as an indicator of other forms of collaboration among countries and of the attractiveness of scientific fields, and explains some properties of the evolution of science (Coccia and Bozeman 2016). But international collaboration also entails costs of time and travel and could imply that when countries share an agenda there is a risk that scientists could ending up working only on issues that peer consensus defines as the most interesting (Adams 2012).

In the literature on international scientific collaboration,[2] several papers focus on the driving factors of international research collaboration (Frame and Carpenter 1979; Luukkonen et al. 1992; Wagner 2005; Hoekman et al. 2010; Melkers and Kiopa 2010; Coccia and Bozeman 2016). They show that in international scientific collaboration, many factors interact (Zitt et al. 2000) and their relative importance depends on the level of aggregation analysed (Luukkonen et al. 1992).

At the national level, the size of the country is a common factor explaining international collaboration, with larger countries being less inclined to participate in international collaboration than smaller ones (Luukkonen et al. 1992; Mattsson et al. 2008). Political, linguistic, historical, geographic, and cultural proximities have been identified as drivers of international collaboration across countries (Cheng et al. 2019). For instance, Adams (2012) pointed to regional and linguistic proximities as relevant factors

[2] See Cheng et al. (2019) for a recent review of the literature on international collaboration.

for explaining regional international collaboration research networks, facilitating a better transfer and combination of knowledge. Frame and Carpenter (1979) identified four clusters of countries with a similar volume of collaboration and similar patterns of international collaboration influenced by economics and social-cultural, geographical, and political factors. Luukkonen et al. (1992) highlighted the role of size, geopolitics, history, language, and cultural similarity in explaining different clusters of collaborative networks among the thirty most scientifically productive countries in the world. Zitt et al. (2000) found a mixture of cultural, linguistic, economic, and geographical factors affecting the international collaboration behaviour of the five largest science producers. Schubert and Gränzel (2006) analysed the preference patterns of the thirty-six most scientifically important countries and found that geopolitical, cultural, and linguistic factors were determinant in the configuration of co-authorship, cross-references, and cross-citations preferences. Pan et al. (2012) analysed citation and collaboration networks across cities and countries, finding that long-distance interactions follow gravity laws. The authors found a lineal relationship between research and development (R&D) funds and the total impact of research on a country, while the average impact showed a threshold effect.

Globalization in scientific research facilitated by the development of communication and information technologies (Gränzel and Schubert 2004; Choi 2012) as well as government policies supporting international research collaboration (Luukkonen et al. 1992; Hoekman et al. 2010; Kwon et al. 2012) have also been pointed out as determinants of the increased level of scientific collaboration at longer distances.

The diffusion of scientific capacity leads to the building of scientific capacity of developing countries and obtaining mutual benefits and excellence also motivate international collaboration (Wagner and Leydesdorff 2005; Chinchilla-Rodríguez et al. 2018). For instance, Wagner et al. (2001) found that scientifically advanced countries collaborate among themselves in all major scientific fields, but also with scientifically proficient and developing countries, and to a lesser extent with those of lagging countries; collaboration between scientifically proficient and developing countries was growing. Gazni et al. (2012) concluded that the scientific development of countries and their economic development affect their behaviour in international collaboration, with highly scientifically developed countries more likely to collaborate internationally. Zitt et al. (2000) found that the five most scientifically advanced countries collaborated preferentially in strong research fields common to two countries, followed by collaboration in strong fields for one of them, and to a lesser extent in weak fields for two countries in their study. Moed (2016) built a bibliometric model for assessing the scientific development of a country and stated that the share of internationally co-authored papers varies with the phases of a country's scientific development. Choi (2012) analysed international scientific collaboration networks among thirty OECD advanced countries during 1995-2010 and confirmed the existence of a core-periphery pattern with a rapid increase in international collaboration among peripheral countries and a decrease in the dependence of these countries on the cores. Leydesdorff and Wagner (2008) analysed a global research network composed of 194 countries and found that during 2000-2005, there was an increase in the strength of core countries constituted by the fourteen most cooperative countries, while the rest remained peripheral.

The growth in international collaboration involves all sciences, but patterns of collaboration differ according to scientific fields (Bozeman and Corley 2004), reflecting the different modes of research between basic and more applied sciences (Newman 2004). Several papers have focused on international scientific collaboration at the field level with mixed results depending on the data, the definition of disciplines, and the methodology used (Wagner et al. 2017). For instance, Abt (2007) analysed multinational co-authored papers in 2005, and found that frequencies of international papers varied significantly between fields ranging from astronomy (with the highest) to surgery (with the lowest). Newman (2004) analysed the patterns of collaboration and the structure of three networks of scientific collaboration (biology, mathematics, and physics) finding clear differences among them. Mattsson et al. (2008) found that physical, chemical, and earth sciences were the fields with the highest level of international collaboration. Gazni et al. (2012) analysed 22 fields during 2000-2009 and found that space science, geosciences, and physics were the disciplines with the highest levels of international collaboration, while the social sciences, psychiatry/psychology, and clinical medicine were at the opposite extreme. Coccia and Wang (2016) analysed the evolution of patterns of international collaboration across seven scientific fields during 1997-2012. They detected an increase in volume of international collaboration for all scientific fields, but with stability in the general architecture of international collaboration pattern for scientific fields over time.

Some motives for international collaboration seem to be discipline-specific (Schubert and Sooryamoorthy 2010). In the international collaboration literature, social factors (such as the universal character of the discipline or the search for acknowledgement from the scientific community), economic reasons (such as the need to share resources and facilities), cognitive reasons (such as the need to coordinate observations, share data and ideas), the nature of the objects studied, and the interdisciplinary nature of some fields have been highlighted as motives for differences in international collaboration across scientific fields (Frame and Carpenter 1979; Luukkonen et al. 1992; Abt 2007; Wagner 2005; Mattsson et al. 2008).

On the other hand, diverse papers highlight the higher international orientation of more basic science than applied science fields (e.g., Frame and Carpenter 1979; Luukkonen et al. 1992), although the pattern seems to be evolving toward a greater international presence in the latter. Coccia and Bozeman (2016) analysed international scientific collaboration for selected countries from 1997 to 2012 and found higher levels of relative growth in applied than in basic fields. The authors concluded that the increase in the international orientation of applied fields may be mainly explained by the emergence of new core research areas in science that largely stem from applied fields such as biochemistry or molecular biology, and by the role of collaboration networks in determining the evolution of scientific disciplines. Regarding the latter, social dynamics of science approach considers the evolution of scientific disciplines and the emergence of new fields as a process driven by social interactions from social communities in a collaboration network (Sun 2013). Collaborative networks based on co-authorship displaying social connections among researchers can be used to investigate social characteristics of science (Mao et al. 2017). As Newman (2004:5200) notes "The coauthorship network is as much a network depicting academic society as it is a network depicting the structure of our knowledge." International research collaboration is a global network (Wagner et al. 2015) playing a crucial role in the dynamics and evolution of science, as social construction of science approach has highlighted (Coccia and Bozeman 2016).

In addition, convergence between scientific fields also contributes to explaining the evolution of science (Coccia 2018). For example, Wagner et al. (2017) analysed the pattern of collaboration for six specialties in 2008 and 2013 and found that the six specialties converged toward similar levels of international collaboration activity and supported convergence at the global level (for all specialities together). These findings suggest that "the global network has a culture, pathways, and norms of communication specific to its structure, and diverging from national, regional, or disciplinary norms" (Wagner et al. 2017: 1646). Coccia and Wang (2016) found convergence of the patterns of international scientific collaboration across different scientific fields as well as between basic and applied sciences over time. The authors indicate the emergence of new scientific fields, mainly in the applied sciences, and social interaction among researchers as the main factors that lead to this convergence.

Finally, the term convergence is an important issue in economic growth studies. Diverse hypotheses have been established in relation to the evolution of the distribution patterns of per capita income within growth theories framework. The absolute convergence hypothesis assumes that per capita income of countries will tend to converge to a common steady state, while conditional convergence holds that the per capita income of countries will converge in the long run if they have similar structural characteristics (e.g., technology, preferences, population growth, etc.) (Barro and Sala-i-Martin 1992; Galor 1996). In relation to the latter, the club convergence hypothesis states that countries with similar structural conditions will converge together if they have the same initial conditions (Galor 1996).[3] In a similar way, this paper aims to investigate whether during the analysed period the countries of our sample have followed a full convergence pattern, or have diverged or have converged in clubs in relation to their international scientific collaboration activity. Interestingly, in the latter case, the methodology applied in the study allows us to determine endogenously, that is, without any prior criteria, the composition of the clubs.

3. Data and Methodology

3.1 Data

In this paper, international research collaboration is measured by international co-authored papers at the country level provided by the National Science Foundation dataset (NSF 2014)[4] for 1997-2012. In this dataset, internationally co-authored papers are those with one or more institutional address from different countries. Articles are assigned to a country on the basis of the institutional addresses listed in the article using the full count method—that is, each collaborating country is credited with one count (see NSF 2014 for more details).

In this paper the patterns of international collaboration in publications have been analysed at the national level for all fields combined and also separately for the basic and applied science fields. The

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[3] While the hypotheses of absolute and conditional convergence are based on models that assume the uniqueness of equilibrium, the club convergence hypothesis assumes that the economic system is characterized by multiple equilibriums.

[4] In the National Science Foundation dataset article counts are from the set of journals covered by the Science Citation Index (SCI) and Social Sciences Citation Index (SSCI) (NSF, 2014).

thirteen fields considered in the NFS (2014) data were classified in this study as basic (astronomy, chemistry, mathematics, and physics) and applied research fields (agricultural sciences, biological sciences, computer sciences, engineering, geosciences, medical sciences, other life sciences, psychology, and social sciences), following the classification of Coccia and Wang (2016).[5]

Regarding the countries included in the analysis, NSF (2014) data comprises 40 developed and developing countries.[6] The sample includes Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Czech Republic, Denmark, Egypt, Finland, France, Germany, Greece, Hungary, India, Iran, Ireland, Israel, Italy, Japan, Mexico, New Zealand, Norway, Poland, Portugal, Russia, Saudi Arabia, Singapore, South Africa, South Korea, Spain, Sweden, Switzerland, Taiwan, The Netherlands, Turkey, the United Kingdom, and the United States.

3.2 Methodology

This paper analyses convergence in the number of internationally co-authored scientific articles in per capita terms across a selected group of countries during the period 1997-2012. As was described in Section 3.1, the number of internationally co-authored papers at the country level has been provided by the National Science Foundation dataset (NSF 2014). To obtain the number of international co-publications per million of inhabitants of each country, we used population data from the World Bank.

In order to analyse the convergence patterns in international collaboration across the countries of the sample, we employed an econometric method based on the Phillips and Sul (2007, 2009) log t test. This methodology has a clear advantage over other alternatives by allowing endogenous identification of groups of countries by unspecified factors that determine the formation of convergence clubs. Phillips and Sul (2007, 2009) developed a log *t* test to capture the heterogeneity in panel data; they proposed a nonlinear time-varying factor model for testing the convergence hypothesis and the identification of convergence clubs. The variable under study, P_{it} (in our case the number of internationally co-authored scientific articles in per capita terms), is explained by two components:

$$P_{it} = \beta_{it} \mu_t \quad (1)$$

where β_{it} is a time-varying idiosyncratic element that measures the deviation of country *i* from the common path defined by μ_t. The factor β_{it} can then be represented as:

$$\beta_{it} = \beta_i + \sigma_i \varphi_{it} L(t)^{-1} t^{-\alpha} \quad (2)$$

Where $\varphi_{it} \sim iid(0,1)$ and β_i is fixed. L(t) is a varying function and when $t \to \infty$ then L(t) → ∞. The null hypothesis of convergence implies that β_{it} converges to β_i for all $\sigma \geq 0$. Consequently, we can define the

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[5] The authors classify scientific fields based on the consensus in the previous literature, pointing out that chemistry and biological sciences were the most discussed sectors, choosing to include the first within the basic field and the second within the applied field.

[6] Regarding international collaboration, the National Science Foundation (NSF 2014) dataset includes countries with more than 1% of internationally co-authored articles in 2012.

hypothesis to be tested as follow:

$$H_0: \beta_i = \beta_i \text{ and } \alpha \geq 0; H_1: \beta_i \neq \beta_i \text{ for some and/ or } \alpha < 0 \quad (3)$$

Likewise, Phillips and Sul (2007) propose modelling the transitional parameter h_{it}, which is the relative transition coefficient in order to test for convergence in the panel data and keep the following form:

$$h_{it}=\frac{P_{it}}{\frac{\sum_{i=1}^{N} P_{it}}{N}}=\frac{\beta_{it}}{\frac{\sum_{i=1}^{N} \beta_{it}}{N}} \quad (4)$$

This measures the weighted coefficients β_{it} in relation to the panel data so that the variable h_{it} is called the relative transition path, and traces an individual path for each country *i* relative to the average panel data. Thus, h_{it} measures the trajectory of each country *i* from the starting position relative to the path of common growth. When there is common behaviour in the path of growth between countries, $h_{it}=h_t$, it could find a convergence club between that group and, in the same way, could trace the path of common growth of the club on the panel data.

Studying convergence in a panel data set has several appealing features. Since the model traces an individual path for each country *i* relative to the average panel of data, we can distinguish empirically different degrees of convergence; the regression coefficient β provides a scaled estimator of the speed of convergence parameter.

Finally, the absolute convergence hypothesis is based on the fact that H_t tends to zero. To study it, if we consider the following model to fit the data:

$$\log\left(\frac{H_1}{H_t}\right) -2\log(\log t)=a+\beta \log t+u_t, \qquad t=[rT], [rT]+1,\ldots,T \quad (5)$$

if $\beta<0$, the absolute convergence hypothesis is rejected. Based on Monte Carlo simulations, Phillips and Sul (2007) suggest using r=0.3 for sample sizes below T=50.

The next step is to measure, with a suitable statistic, the degree of reliability of the value obtained for β.

If the global convergence hypothesis is rejected, then it goes on to identify possible convergence clubs. To this end, an iterative algorithm developed by Phillips and Sul (2007) is applied; the results of this algorithm have a significance level of 5%. The iterative procedure for identifying convergence clubs is summarized in four steps: the first step is to order the panel data from highest to lowest based on the observations of the last period; the second step is to select k in the panel countries to form each club. This begins to form groups of countries from the highest value of each variable in the last period so that the groups will be formed by a number of countries $2 \leq k < N$. The size of the group is determined based on the maximum t_k, with $t_k > -1.65$. In the third step, if in the previous step two countries meet the established criterion, the process will continue, adding countries in the order they appear in the panel data, which is already sorted, while the data continue to meet the criterion. When the data no longer meet the criterion, it has found the first club. In the fourth step, for the remaining countries we iteratively applied steps 1 to 3 in order to find successive clubs. The countries show divergent behaviour if no core group can be found.

4. Results

The results are presented in two subsections. Firstly, the results of our descriptive analysis of the data are displayed. Secondly, the results of the applied log t test methodology are shown.

4.1 Descriptive analysis

In this section we provide the results of descriptive analysis of international research collaboration data for the countries in our sample. Firstly, we do a descriptive analysis comprising all research fields combined, then we distinguish the results between basic and applied research fields, and finally we consider individual scientific fields.

Table 1 displays data about international co-authored papers by country in 1997 and 2012, and for the entire period, for the countries of our sample. Countries are ranked in descending order by the total number of international papers in the period 1997-2012. The US and Canada in North America; Germany, the United Kingdom, France, Italy, Spain and the Netherlands in the European Union; and the Asian countries Japan and China are the ten countries with the highest number of internationally co-authored papers in the analysed period.

As shown in Table 1, over the 15-year time span the percentage of co-authored papers by multiple nations has increased; about 25% of the world´s scientific papers were internationally co-authored in 2012, whereas it was about 16% in 1997. In the analysed period, all countries have shown this same trend, increasing their share of internationally co-authored publications; exceptions are China and Poland, which have stagnated, and Brazil and Iran, which have decreased their international collaboration activity. Data show that 70% of the analysed countries had more than half of their articles internationally co-authored in 2012, ranging from 50.2% for Canada to 80.2% for Saudi Arabia; the rest of the countries had between 20% and 50% of their national papers internationally co-authored, ranging from 24.8% for Iran to 49.2% for Argentina. In 1997, only two countries, Hungary and Portugal, presented international collaboration rates above 50%, 34 countries had between 20% and 50% of their national papers internationally co-authored, and four countries (the US, Taiwan, Japan, and India) had less of 20% of their papers internationally co-authored in that year.

Table 1 about here

As mentioned in Section 2, several papers emphasise that scientific collaboration patterns at the international level can be considered as network effects with its internal dynamics (Leydesdorff and Wagner, 2008). The National Science Foundation dataset (NSF 2014) provides the number of co-authored papers between each pair of countries from 1997 to 2012. Simple metrics from social network analysis (SNA) allow us to describe the changes in the global network configuration of international collaboration over the 15-year time span using this information.[7] We applied Salton´s measure, calculated as the number

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[7] We used UCINET 6.0 software (Borgatti et al., 2002) for obtaining network metrics and NewDraw for network visualization.

of co-authored papers between country *i* and country *j* in the year *t*, weighted by the total number of papers of country *i* and country *j* in this year, to obtain normalized matrices.[8]

Figure 1 shows international collaboration networks in terms of Salton´s measure similar to or above 4.5% for 1997 (a) and 2012 (b).[9] The international collaboration network among countries is composed of 40 nodes (countries) with 747 ties in 1997 and 780 ties in 2012,[10] coinciding with the number of maximum possible ties. The collaboration network is highly dense, with all countries collaborating with each other in 2012 (in 1997 the network density was 95.8%), and an average degree of 39, indicating that all possible links are realized (in 1997 the average degree was 37.35). As we can see, collaboration networks have experienced an increase in the number and strength of linkages over the 15 years in the sample. A simple view of collaboration network graphs suggests the existence of clusters of regions such as Latin America countries, western European countries, Middle Eastern countries (Egypt–Saudi Arabia), or Asia-Pacific countries previously highlighted in other studies (e.g., Glänzel 2001; Adams 2012; Zhou et al. 2013). It shows the importance of geopolitical, cultural, and linguistic factors for international collaboration across countries (Zhou et al. 2013).

The core-periphery analysis[11] reveals that 10 European countries—Belgium, Denmark, France, Germany, Italy, the Netherlands, Spain, Sweden, Switzerland, and the United Kingdom—and the United States were cores in the network in 1997, collaborating together extensively. In 2012, five European countries (including three new member states) were added to the group of the 11 most cooperative countries—Austria, Czech Republic, Greece, Hungary and Poland—while one, Belgium, was added to the peripheral countries.[12]

Figure 1a about here

Figure 1b about here

The paper also analyses the international co-authored papers at the country level, distinguishing between basic and applied research fields. Tables 2 and 3 display countries ranked in descending order by their total international co-authored papers in basic and applied fields for the total period, respectively. It can be seen that the 10 countries with the highest number of articles in international co-authorship are the

[8] Salton´s measure is a direct similarity measure widely applied to normalize co-occurrence data (van Eck and Waltman, 2009) (see for instance, Luukkonen et al. 1993; He, 2009; Schubert and Sooryamoorthy 2010; Wagner et al. 2017).

[9] This cutoff point has been used in other studies on collaboration networks applying network analysis techniques (e.g., Choi 2012); it allows a more useful visualization of the collaboration network.

[10] The number of maximum ties is calculated as (40*39)/2=780 because the matrix is symmetric.

[11] Core/Periphery fit (correlation) was 81.28% in 1997 and 75.25 % in 2012.

[12] The importance of multinational collaboration between these new cores has been emphasised in other studies, for instance, Gorraiz et al. (2012).

same for the basic and the applied sciences, with the exception of Russia (for basic sciences) and Australia (for applied sciences).

Throughout the analysed period, the percentage of papers in international co-authorship has increased in both basic and applied fields, although to a greater extent in the latter (6.2% and 10.5%, respectively). 26% of the world's scientific articles in basic sciences were internationally co-authored in 2012, while in 1997 the total was approximately 20%; these figures were 24.4% and 14% for applied science. As mentioned above (see section 2), the new emerging scientific fields and social interactions among scientists are some of the main factors that explain this higher growth in international collaboration for the applied sciences (Coccia and Bozeman 2016).

Over the time span of 15 years all countries showed this trend, increasing their participation in international co-authored publications in basic and applied fields; exceptions are China, Brazil, and Iran, which have maintained their international collaboration in basic fields but have decreased it in applied fields. Poland has slightly decreased its international collaboration in basic sciences, and South Korea has slightly decreased it in applied research fields.

The changes can be synthesized in the following: in 2012, in 72.5% of the countries more than half of the articles in the basic science fields showed international co-authorship, 20% of the countries had between 30% and 50%, and in 7.5% fewer than 30% of their papers were internationally co-authored. In 1997, these figures were 35%, 42.5%, and 22.5%, respectively, and within the latter, three countries had a percentage lower than 20%. Regarding the applied sciences, in 2012, in 55% of the countries more than half of their articles were in international co-authorship, 30% of countries had between 30% and 50%, and 15% fewer than 30% of their documents were internationally co-authored. In 1997, these figures were 2.5%, 67.5%, and 30%, respectively, with five countries having a percentage lower than 20%.

Table 2 about here

Table 3 about here

Figure 2 describes the distribution of internationally co-authored papers across research fields in 1997 and 2012. Two applied research fields, the biological sciences and medical sciences, and two basic fields, physics and chemistry, are the four largest fields in the production of internationally co-authored papers; together they represent two-thirds of the total international papers published in 2012 and three-quarters of those published in 1997. Focusing on the evolution of the four fields with the largest production of internationally co-authored papers, biological sciences and physics lost weight in the total, while the percentage of internationally co-authored papers in medical sciences and chemistry grew slightly.

Figure 2 about here

Finally, Table 4 displays the degree of internationalization of each research field. In 2012 astronomy occupied the first place, with more than half of its papers internationally co-authored (at the beginning of the period this was also the international field with the most internationally co-authored papers). Three research fields (geosciences, computer sciences, and mathematics) had more than 30% internationally co-authored papers; seven research fields (physics, biological sciences, agricultural sciences, medical sciences, engineering, psychology, and chemistry) had between 20% and 30%; and only two fields (social sciences and other life sciences) had fewer than of 20% of the internationally co-authored papers. All research fields have increased the percentage of internationally co-authored papers, although with higher growth rates in applied fields than in basic fields.

4.2 Log t test Results

In this section, we examine the patterns of convergence in international scientific collaboration activity for the set of 40 countries during 1997-2012. First, we study the patterns of convergence in international scientific collaboration activity across countries considering all fields combined; that is, we obtain the country's number of international co-authored papers as the aggregated value for all scientific fields, and then we do the analysis separately for the basic and applied science fields.

To analyse the convergence in international co-authored papers per capita across countries for the aggregate of all scientific fields from 1997 to 2012, the Phillips and Sul (2007) log *t* test was applied. As result the overall convergence hypothesis is rejected at the 5% significance level. Then we applied the cluster mechanism procedure and identified four convergence clubs and three divergence countries. Table 5 presents the results from the Phillips and Sul (2007) procedure.

The first convergence club contains 11 countries; they published the largest number of articles with international co-authorship per million inhabitants, 857.25 on average in 2012. In the log *t* test procedure, Club 1 experienced the greatest degree of convergence within clubs, with an estimated speed of convergence of 0.1462 ("β" =0.2925). The corresponding t statistics clearly meet the criterion of being greater than -1.65 (see statistics in Table 5), reaching the highest value, so we can say that they are the most cohesive clubs for internationally co-authored scientific articles per capita. The second convergence club includes nine countries that published an average of 469.68 articles with international co-authorship per million inhabitants in 2012. In this case, the estimated speed of convergence was 0.1145 ("β" =0.2289), with a corresponding t statistic significantly different from zero. These first two clubs, Club 1 and Club 2, are formed by European countries (all in the sample, except Hungary and Poland), Australia, Canada, New Zealand, Singapore, and Israel. Most of them belong in the high income or upper middle income brackets in the World Bank definition.[13] Most of the core countries of the global collaboration network identified in sub-section 4.1 belong to these two clubs.

The third convergence club contains six countries. These countries published 181.88 articles with international co-authorship per million inhabitants on average in 2012. In the log *t* test procedure, Club 3 has an estimated speed of convergence of 0.0449 ("β" =0.0897), and the corresponding t statistic was 1.4905 (Table 5). The fourth convergence club includes 11 countries that published an average of 43.33 articles

[13] The World Bank classifies countries into four groups economically: high income, upper middle income, lower middle income, and low income (World Bank, 2010).

with international co-authorship per million inhabitants in 2012; in this case the estimated speed of convergence was near zero, with a corresponding negative value t statistic but still greater than the critical value. This was the least cohesive group. Countries in Africa, Asia,[14] South America and the BRIC[15] countries, as well as Hungary and Poland, form the third and fourth clubs, belonging to a large extent to countries classified as middle income and low income by the World Bank.

Finally, Switzerland, Italy, and the United States are divergent countries. Switzerland showed a divergent pattern because it has a very different behaviour both in its starting conditions and in the evolution of its growth that is much higher than the rest of the countries in terms of the number of articles per capita in international scientific collaboration. The divergent behaviour of Switzerland could be explained by its strong research internationalization stemming from the location of many international scientific establishments such as the CERN Europe's particle physics lab or the World Health Organization (Adams 2013). Italy and the United States, although their starting conditions were those of Club 2, have not been affected by the growth path of this club, which has made them divergent countries for the whole of the sample in the period analysed. In the case of Italy, this may be because it has fallen behind in international collaboration with respect to the most scientifically advanced European countries since the mid-2000s (Daraio and Moed 2011). In the case of the US, although it has increased its levels of international research collaboration, it continues to be less internationally collaborative than scientifically advanced countries located in Western Europe (Adams 2013). This may be related to its size, since, as we mentioned in Section 2, large countries seem to exhibit a lesser propensity to collaborate internationally than small ones.

Table 5 about here

Figure 3 displays the relative transition paths of the four clubs showing the tendencies across groups. Under the assumption of convergence for the full panel of countries, the relative transition path should tend to unity—that is, all should converge to the same level of internationally co-authored scientific articles per capita. However, assuming club convergence, the relative transition paths of the different clubs tend to different values. In this case, it seems that the third club is around average; the first and the second clubs are above average and the fourth is below average. Club 1 and Club 2 seem to maintain an equivalent distance throughout the period. Club 4, which is clearly below average, seems to show an upward trend. Nevertheless, the transition paths of the four clubs are slightly approaching throughout the period, indicating a possible convergent trend among clubs.

Figure 3 about here

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[14] Haustein et al. (2011) found that Asian-Pacific countries such as China, Japan, South Korea, and Taiwan, with high scientific output, had a smaller percentage of international co-publication.

[15] The increase in scientific collaboration between BRIC countries during the 2000s has been shown in diverse studies (for instance, Finardi, 2015).

As previously mentioned, the scientific fields differ in their international collaboration patterns. With the objective of analysing if there are differentiated convergence patterns between basic and applied scientific fields, we applied the Phillips and Sul (2007) procedure to both sets of panel data. The overall convergence hypothesis is rejected at the 5% significance level, but patterns of convergence clubs were found in both cases. From an overall perspective, it seems that the patterns of convergence are not very different between both types of fields, but if we go into details there are some issues that should be highlighted to differentiate the convergence patterns in international scientific collaboration in basic and applied sciences between countries.

In the case of basic sciences (Table 6), when we applied the cluster mechanism procedure, five convergence clubs and no divergent countries were identified, unlike what happens in all scientific fields together. The first convergence club contains four countries (Switzerland, Singapore, Finland, Ireland); they are the countries that published the largest number of articles with international co-authored papers per million inhabitants, 309.07 on average in 2012. In the log *t* test procedure, Club 1 experienced an intermediate value degree of convergence within clubs with an estimated speed of convergence of 0.0183 ("β" =0.0366). The second convergence club includes five countries (Denmark, Sweden, Austria, Belgium, Portugal). These countries published an average of 233.21 articles with international co-authorship per million inhabitants in 2012; in this case, the estimated speed of convergence was 0.0215 ("β" =0.0430) with a corresponding t statistic significantly different from zero. These first two clubs, Club 1 and Club 2, are formed by European countries plus Singapore, all of them high income by the World Bank classification. The third convergence club contains 13 countries; this is the largest club and the one with the highest speed of convergence. Club 3 takes an estimated speed of convergence of 0.1657 ("β" =0.3314), and the corresponding t statistic is 2.7582, which is the greatest value among the clubs, and it is the more cohesive one. Club 3 includes Western European countries, Australia, Canada, New Zealand, the Czech Republic, and Israel. These countries published 160.21 articles with international co-authorship per million inhabitants on average in 2012. The fourth and fifth convergence clubs include nine countries each. Both have a weaker convergence, which can be deduced from the values reached by t statistic and the speed of convergence (see Table 6). In addition, in the case of these last two clubs, the averages of articles with international co-authorship per million inhabitants on average in 2012 are the lowest, 67.78 and 14.76, respectively. All the countries on the sample that belong to upper middle income and low middle income in the Wold Bank classification are in these last two clubs.

As we can observe in both Table 6 and Figure 4, in the first three clubs, the greater in average articles per capita and with transitions path above the average, include the same countries as clubs 1 and 2 in all fields plus Switzerland and Italy, which were divergent when the log t test was applied to all the sciences; the United Stated is in a club below the average (club 4) for the basic science but not for the applied fields (Club 3); something similar happens for Japan. It is known that larger countries have fewer incentives to engage in international collaboration because they have a large number of scholars, scientific staff, universities, and learning space in which to work together (Glänzel and Schubert 2005[16]; Haustein et al. 2011; Luukkonen et al. 1992).

Table 7 shows the results for convergence clubs in international research collaboration for the applied sciences. When we applied the log *t* test procedure, four convergence clubs and three divergent countries (Switzerland, Argentina and India) were identified, quite similar to the set of all scientific fields. Nevertheless, Hungary, South Korea, Taiwan, and Chile hold a better position; they go from being below the average for all the sciences to being above in the case of the applied sciences, while the opposite happens in the case of Japan.

The first convergence club contains seven countries (Denmark, Sweden, Norway, the Netherlands, New Zealand, Australia, and Singapore). They are the countries that published the largest number of articles with international co-authorship per million inhabitants, 694.16 on average, in 2012. Running the log t test procedure, we see that Club 1 has the highest degree of convergence within clubs, being the most cohesive club with an estimated speed of convergence of 0.1016 ("β" =0.2031). The second convergence club includes six countries (Finland, Belgium, Austria, Canada, Ireland, and the United Kingdom), which published an average of 516.42 articles with international co-authorship per million inhabitants in 2012; in this case the estimated speed of convergence was the highest, 0.5039 ("β" =0.2519). The third convergence club contains 13 countries, the largest club. This club exhibits an intermediate speed of convergence of 0.1057 ("β" =0.3314). Countries in this club published on average 208.86 articles with international co-authorship per million inhabitants in 2012. The fourth convergence club, which has 11 countries, is the weaker one in terms of convergence. This can be deduced by the values reached by the t statistic, negative but still satisfying the criterion (see Table 6). In addition, the average of articles with international co-authorship per million inhabitants on average in 2012 is the lowest, 35.43.

Figures 4 and 5 display the relative transition paths for the five convergence clubs in the basic science fields and the four convergence clubs in the applied science fields, respectively. For the basic fields, three clubs are above the average and two below, while three are above the average and only one is below it in the case of the applied fields. These results seem to suggest a somewhat more convergent behaviour across countries in applied than in basic sciences. When the composition of clubs is compared in both cases, a larger group of countries belong to a more “advanced” club for applied fields than for basic sciences. It is consistent with the evolution of science toward a high level of international collaboration in the applied fields (Coccia and Bozeman 2016; Coccia and Wang 2016), as discussed above in Section 2.

In addition, in the case of the basic sciences there seems to have been a change in the convergence process; since 2002, the countries that behaved as a single club were divided in two, the first formed by Switzerland, Singapore, Finland, and Ireland; and the second for Denmark, Sweden, Austria, Belgium, and Portugal, putting the first group of countries at the top tier in the publication of articles with internationally

[16] As Glänzel and Shubert (2005:336) point out: “co-authorship domesticity is clearly influenced by at least two main factors: country size (it is evidently easier for a US or UK researcher to find domestic collaboration partners than for a colleague from Hungary or Belgium) and country remoteness (made up of geographic, linguistic, political, etc., components)”.

co-authored publications per million inhabitants. Further, in Figures 4 and 5 we can see that the transition paths of the five and four clubs, respectively, are slightly approaching each other throughout the period, which suggests a convergent trend in the basic fields as well as the applied fields between clubs.

Finally, the absence of full convergence indicates that there exist idiosyncratic factors in each country and in applied and basic fields in the sample that are relevant to the convergence pattern observed in this paper. Mainly, scientific and technological capabilities of countries, proximities (geopolitics, economic, cultural, and linguistic), economic factors, and the current evolution of science characterized with a greater growth in international collaboration in the applied fields, form a complex plexus of factors that, jointly with initial conditions, could affect the patterns of convergence of international research collaboration across countries in basic and applied fields. A deeper empirical analysis remains to clarify the specific effect and relevance of these factors to explain the formation of these convergence clubs.

Table 6 about here

Figure 4 about here

Table 7 about here

Figure 5 about here

5. Conclusions

Currently, scientific and technology knowledge constitutes a basic pillar of the economic and social development of nations. Increasingly, scientific research is carried out by large, multidisciplinary and international teams as an attempt to respond to the challenges that current societies present (Bozeman et al. 2013). Due to the importance of international collaboration for productivity and the impact of the scientific knowledge generated, the key issue is to have a better understanding of the spatial pattern of international scientific collaboration among countries, analysing whether its growth path over time has tended toward convergence or divergence.

To obtain a greater knowledge of this question, this article analyses the pattern of convergence among a wide sample of countries for the period 1997-2012, applying Phillips and Sul's (2007, 2009) methodology to international collaboration data in a novel way. With the data obtained on international scientific collaboration through articles co-authored by researchers from other countries, the empirical analysis focuses on three issues. First, the spatial pattern of international scientific collaboration is analysed; second, the pattern of convergence is analysed for the aggregate of all scientific fields; and finally, the analysis of convergence is made for the basic and applied sciences fields separately.

The results of our analysis for all fields combined show a convergence in four clubs instead of a global convergence among countries in relation to the number of internationally co-authored papers per capita. This convergence in clubs in not surprising since, although there has been a general increase in international collaboration in most countries, not all countries began from the same initial conditions. Following the club convergence hypothesis, countries with similar structural conditions regarding factors determining international scientific publications can belong to one club or another depending on their initial conditions. In addition, our results seem to indicate that there is a trend toward a gradual convergence among the three clubs with the highest number of international papers in co-authorship per capita, while a group of countries is still far behind the others.

The analysis of basic and applied science fields separately seems to suggest that the dynamics of growth and convergence among countries for international scientific collaboration has been greater in applied sciences than in basic sciences. Although the convergence has been in clubs, if we observe the results of the application of the log t test comparatively, a greater number of countries belong to clubs whose transition curves appear below the average in the case of the basic sciences than in the case of the applied sciences. In other words, for the basic sciences there are a greater number of countries that could be classified as international collaboration-lagging countries than there are for the applied sciences. This differentiated behaviour could be due to the greater social interaction in the applied sciences since they are more interdisciplinary, generate a greater number of emerging research fields, and their practical applications lead them to greater dynamism (Battard, 2012, Coccia et al. 2012; Jeffrey, 2003), which has led them to grow in international collaboration relatively more than the basic science fields (Coccia and Bozeman 2016; Coccia and Wang 2016).

Indeed, the differences in the dynamics between the basic and applied sciences fields are noteworthy. The basic sciences have a longer history in international scientific collaboration because their theoretical problems have universal interest (Luukkonen et al. 1992). Also, one needs to take into account the so-called "emphasis" effect argued by Wagner (2005)—that is, that the basic sciences are not so commonly found in universities and research centres in developing countries. In addition, in basic sciences, although there is a large number of works with international scientific collaboration, they are shared by a smaller group of researchers. Conversely, it seems that the dynamics in the applied sciences correspond more to an inclusive development than an exclusive centre-periphery pattern. This makes sense since the applied sciences are less elitist in the development of knowledge and tend to be more dynamic and open systems (Leydesdorff et al. 2013). This dynamic helps participation in the international collaboration of countries that were previously considered "country remoteness" (Glänzel and Schubert 2005) or lagging countries (Wagner et al. 2001). However, the transition paths of the five clubs for the basic sciences and of the four clubs for the applied sciences are approaching each other slightly throughout the period, indicating a convergent tendency among the clubs for both basic and applied sciences.

Finally, the empirical analysis carried out in this document has provided a clear picture of the dynamics of growth and convergence in international scientific collaboration among countries for all fields combined, and for the basic and applied fields. However, the study has some limitations. It analyses collaboration through co-authorship, but scientific collaboration is a broad concept that encompasses multiple forms (Chinchilla- Rodríguez et al. 2018). Our results also could be limited by the period of time considered in this analysis, since it could be considered as a relatively short time in which to analyse convergence. However, despite the previous limitation, the *log t test* methodology has been used in previous papers for analysing economic convergence with similar short time periods (e.g., Monfort et al. 2013; Bartkowska et al. 2012; Borsi et al. 2015). The results offered refer to scientific fields aggregated (all combined or basic and applied fields), but not at the disaggregated level. Therefore, an extended empirical analysis for a longer period of time and by each scientific field separately could give a more complete vision and could help us better understand international scientific collaboration and the diffusion of international knowledge. Finally, our empirical analysis allows the identification of the convergence clubs, but does not test directly the effect and relevance of the plexus factors that could help to explain the formation of these convergence clubs. This latter exceeds the scope of this study, but future research should emphasize the influence that the factors mentioned in the literature as drivers of international scientific collaboration have played in this process.

The determination of the factors that explain the formation of convergence clubs between countries would provide crucial information that could serve as a guide for scientific policy decisions, whether the reasons for the internationalization policy follow a narrow or a broad research policy paradigm (Boekholt et al. 2009). In any case, as Wagner et al. (2015:1) point out, international scientific collaboration is a network "that adds to and complements national systems," and policy-makers could gain efficiency by learning to maximize the benefits of the network.

6. References

Abt, H. A. (2007). The frequencies of multinational papers in various sciences. *Scientrometrics*, 72 (1), 105-115.

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

Adams, J. (2013). Collaborations: The fourth age of research. *Nature*, 497(7451), 557.

Barro, R. J., & Sala-i-Martin, X. (1992). Convergence. *Journal of Political Economy*, 100(2), 223-251.

Bartkowska, M., & Riedl, A. (2012). Regional convergence clubs in Europe: Identification and conditioning factors. *Economic Modelling*, 29(1), 22-31.

Battard, N. (2012). Convergence and multidisciplinarity in nanotechnology: Laboratories as technological hub. *Technovation*, 32(3–4), 234–244.

Borgatti, S. P., Everett, M. G., & Freeman, L. C. (2002). *Ucinet for Windows: Software for Social Network Analysis*. Harvard, MA: Analytic Technologies.

Borsi, M. T., & Metiu, N. (2015). The evolution of economic convergence in the European Union. *Empirical Economics*, 48, 657–681.

Bozeman, B., & Corley, E. (2004). Scientists' collaboration strategies: Implications for scientific and technical human capital. *Research Policy*, 33(4), 599–616.

Bozeman, B., & Gaughan, M. (2011). How do men and women differ in research collaborations? An analysis of the collaboration motives and strategies of academic researchers. *Research Policy*, 40(10), 1393–1402.

Bozeman, B., Fay, D., & Slade, C. P. (2013). Research collaboration in universities and academic entrepreneurship: The state of the art. *Journal of Technology Transfer*, 38, 1-67.

Boekholt, P., Edler, J., Cunningham, P. & Flanagan, K. (2009). *Drivers of International Collaboration in Research.* Report to European Commission, DG Research. Technopolis BV, Netherlands, April 2009.

Carayannis, E. G., & Laget, P. (2004). Transatlantic innovation infrastructure networks: public-private, EU-US R&D partnerships. *R&D Management*, 34, 1731.

Cheng, K., Zhang, Y. & Fu, X. (2019). International research collaboration: An emerging domain of innovation studies?. *Research Policy*, 48, 149-168

Chinchilla-Rodríguez, Z., Miguel, S., Perianes-Rodríguez, A., & Sugimoto, C.R. (2018). Dependencies and autonomy in research performance: Examining nanoscience and nanotechnology in emerging countries. *Scientometrics,* 115, 1485-1504.

Choi, S. (2012). Core-periphery, new clusters, or rising stars? International scientific collaboration among 'advanced' countries in the era of globalization. *Scientrometrics*, 90, 25-41.

Coccia, M. (2018). General properties of the evolution of research fields: A scientometric study of human microbiome, evolutionary robotics and astrobiology. *Scientometrics*, 117 (2), 1265-1283.

Coccia, M., & Bozeman, B. (2016). Allometric models to measure and analyze the evolution of international research collaboration. *Scientometrics*, 108, 1065–1084

Coccia, M., & Wang, L. (2016). Evolution and convergence of the patterns of international scientific collaboration. *PNAS*, 113 (8), 2057-2061.

Coccia, M., Finardi, U., & Margon, D. (2012). Current trends in nanotechnology research across worldwide geo-economic players. *The Journal of Technology Transfer*, 37(5), 777–787.

Cummings, J., & Kiesler, S. (2014). Organization theory and the changing nature of science. *Journal of Organization Design*, 3, 1-16.

Daraio, C., & Moed, H. F. (2011). Is Italian science declining? *Research Policy*, 40(10), 1380-1392.

European Commission (2010). Communication from the Commission EUROPE 2020. A strategy for smart, sustainable and inclusive growth, COM (2010) 2020, 332010.

Finardi, U. (2015). Scientific collaboration between BRIC countries. *Scientometrics*, 102, 1139-1166.

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

Frenken, K., Hardeman, S., & Hoekman, J. (2009). Spatial scientometrics: Towards a cumulative research program. *Journal of Informetrics*, 3, 222-232.

Galor, O. (1996). Convergence? Inferences from theoretical models. *The Economic Journal*, 106, 1056-1069.

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.

Glänzel, W. (2001). National characteristics in international scientific co-authorship relations. *Scientometrics*, 51(1), 69-115.

Glänzel, W., & Schubert, A. (2004). Analysing scientific networks through co-authorship. In *Handbook of quantitative science and technology research.* Kluwer Academic Publishers, Dordrecht,

Glänzel, W. & Schubert, A. (2005): Domesticity and internationality in co-authorship, references and citations. *Scientometrics*, 65 (3), 323-342.

Gorraiz, J., Reimann, R. & Gumpenberger, C. (2012). Key factors and considerations in the assessment of international collaboration: a case study for Austria and six countries. *Scientometrics*, 91, 417-433.

Haustein, S., Tunger, D., Heinrichs, G. & Baelz, G. (2011): Reasons for and developments in international scientific collaboration: Does an Asia–Pacific research area exist from a bibliometric point of view?. *Scientometrics*, 86, 727–746.

He, T. (2009). International scientific collaboration of China with the G7 countries. *Scientometrics*, 80 (3), 571-582.

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, 662-637.

Jeffrey, P. (2003). Smoothing the waters: Observations on the process of cross-disciplinary research collaboration. *Social Studies of Science*, 33(4), 539–562.

Kwon, K-S., Park, H.W., So, M., & Leydesdorff, L. (2012). Has globalization strengthened South Korea's national research system? National and international dynamics of the Triple Helix of scientific co-authorship relationships in South Korea. *Scientometrics*, 90, 163-176.

Lee, B., Kwon, O., & Kim, H.-J. (2011). Identification of dependency patterns in research collaboration environments through cluster analysis. *Journal of Information Science*, 37(1), 67–85.

Lee, S., & Bozeman, B. (2005). The impact of research collaboration on scientific productivity. *Social Studies of Science*, 35(5), 673.

Leydesdorff, L., Wagner, C. S. (2008). International collaboration in science and the formation of a core group. *Journal of Informetrics*, 2, 317-325.

Leydesdorff, L., Wagner, C. S., Park, H. W., & Adams, J. (2013). International collaboration in science: The global map and the network. El Profesional de la Información, 22(1), 87–94.

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. J. W., Persson, O., & Sivertsen, G. (1993). The measurement of international scientific collaboration. *Scientometrics*, 28 (1), 15–36.

Mao, J., Cao, Y., Lu, K., & Li, G. (2017). Topic scientific community in science: a combined perspective of scientific collaboration and topics. *Scientometrics,* 112, 851-875

Mattsson, P., Laget, P., Nilsson, A., & Sundberg, C.-J. (2008). Intra-EU vs. extra-EU scientific co-publication patterns in EU. *Scientometrics*, 75 (3), 555-574.

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. F. (2016). Iran's scientific dominance and the emergence of South-East Asian countries as scientific collaborators in the Persian Gulf Region. *Scientometrics*, 108, 305-314

Monfort, M., Cuestas, J.C., & Ordóñez, J. (2013). Real convergence in Europe: A cluster analysis. *Economic Modelling*, 33, 689-694.

National Science Foundation. (2014). National Center for Science and Engineering Statistics. http://www.nsf.gov/. Accessed Mayo 2018.

Newman, M.E. (2004). Coauthorship networks and patterns of scientific collaboration. *Proceedings of the National Academy of Sciences of the United States of America*, 101 (Suppl. 1), 5200–5205.

Pan, R. K., Kaski, K., & Fortunato, S. (2012). World citation and collaboration networks: Uncovering the role of geography in science. *Scientific Reports*, 2 (902), 1-7.

Phillips, P. C., & Sul, D. (2007). Transition modeling and econometric convergence test. *Econometrica*, 75, 1771-1855.

Phillips, P. C., & Sul, D. (2009). Economic transition and growth. *Journal of Applied Econometrics*, 24, 1153-1185.

Rostan, M. & Ceravolo, F. A. (2015). The internationalisation of the Academy: Convergence and divergence across disciplines. *European Review*, S1, S38-S54.

Schubert, T., & Glänzel, W. (2006). Cross-national preference in co-authorship, references and citations. *Scientometrics*, 69(2): 409–428.

Schubert, T. & Sooryamoorthy, R. (2010). Can the centre–periphery model explain patterns of international scientific collaboration among threshold and industrialised countries? The case of South Africa and Germany. *Scientometrics*, 83, 181-203

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

Sun, X., Kaur, J., Milojevic, S., Flammini, A., & Menczer, F. (2013). Social dynamics of science. *Scientific Reports*, 3(1069), 1–6.

Thijs, B., & Glänzel, W. (2010). A structural analysis of collaboration between European research institutes. *Research Evaluation*, 19(1), 55–65.

Uddin, S., Hossain, L., & Rasmussen, K. (2013). Network effects on scientific collaborations. *PLoS One*, 8(2), e57546.

Van Eck, N. J., & Waltman, L. (2009). How to normalize cooccurrence data? An analysis of some well-known similarity measures. *Journal of the American Society for Information Science and Technology*, 60(8), 1635-1651.

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

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

Wagner, C. S., Han, W. P., & Leydesdorff, L. (2015). The continuing growth of global cooperation networks in research: A conundrum for national governments. *PLoS One*, 10 (7), e 0131816

Wagner, C. S., Whetsell, T. A., & Leydesdorff, L. (2017). Growth of international collaboration in science: revisiting six specialties. *Scientometrics*, 110, 1633-1652.

Wagner, C. S., Brahmakulam, I., Jackson, B., Wong, A., & Yoda, T. (2001). Science and Technology Collaboration: Building Capacity in Developing Countries? MR-1357.0-WB, Santa Monica, CA: RAND.

World Bank (2010). *The World Bank Annual Report*, 2010.

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, 627–657.

Zhou, P., Zhong, Y., & Yu, M. (2013). A bibliometric investigation on China–UK collaboration in food and agriculture. *Scientometrics*, 97, 267-285.

Table 1. Internationally co-authored papers by country.

	Number of papers internationally co-authored			Percentage of internationally co-authored papers		Change*
	1997	2012	1997-2012	1997 (1)	2012 (2)	2012-1997 (%)
United States	40,419	91,183	1,016,673	19.3	34.7	15.5
Germany	17,963	39,161	450,364	35.5	55.5	20.0
United Kingdom	16,819	39,227	435,295	31.0	55.1	24.2
France	14,067	28,150	334,007	37.3	58.2	20.9
Canada	9,235	21,286	231,098	33.5	50.2	16.6
Italy	8,523	19,697	219,683	36.1	51.1	15.0
Japan	9,011	16,591	219,591	16.4	30.0	13.6
China	3,699	31,081	217,609	25.7	26.6	1.0
Spain	5,188	18,045	167,447	32.7	52.5	19.8
Netherlands	6,105	15,187	155,367	38.1	59.5	21.5
Australia	4,789	16,575	148,699	29.4	52.4	23.0
Switzerland	5,581	13,031	137,984	49.6	69.6	20.0
Russia	6,499	7,413	119,935	29.5	40.6	11.1
Sweden	5,055	10,159	117,578	40.7	62.3	21.6
Belgium	3,672	8,876	96,590	48.2	66.7	18.5
South Korea	1,813	10,079	84,339	27.5	30.8	3.2
Brazil	2,295	7,059	69,501	40.7	38.0	-2.7
Poland	2,883	5,524	68,583	47.3	47.4	0.1
Denmark	2,936	6,455	68,281	47.3	61.5	14.2
Austria	2,393	6,323	65,426	45.5	68.7	23.1
India	1,649	7,332	63,274	16.0	26.1	10.1
Israel	2,869	4,558	59,436	37.5	50.9	13.4
Finland	2,162	4,717	53,392	38.2	60.5	22.3
Norway	1,655	4,799	46,192	42.0	61.0	18.9
Taiwan	1,128	4,659	42,389	17.5	27.8	10.3
Czech Republic	1,467	3,790	39,445	47.9	57.6	9.7
Portugal	869	4,554	38,399	50.1	58.8	8.7
Mexico	1,206	3,315	37,885	41.0	51.8	10.8
Greece	1,214	3,617	36,670	39.3	53.7	14.4
Hungary	1,519	2,648	33,640	53.8	64.0	10.1
Singapore	505	4,359	32,035	32.2	59.4	27.2
New Zealand	1,078	3,156	31,933	33.1	54.6	21.4
Argentina	993	2,783	30,293	33.4	49.2	15.9
South Africa	856	3,352	28,804	31.9	60.5	28.6
Ireland	758	3,033	27,232	43.4	60.2	16.7
Turkey	600	2,997	25,822	21.9	28.9	7.1
Chile	618	2,573	22,409	46.7	67.7	21.0
Iran	136	2,634	15,638	30.9	24.8	-6.1
Egypt	472	2,138	15,182	31.4	55.7	24.3
Saudi Arabia	225	3,048	10,627	28.3	80.2	51.9
World	90,867	211,841	2,338,358	15.6	24.9	9.2

* The change is calculated as the difference between columns (2) and (1).

Table 2. Internationally co-authored papers by basic field by country.

	Number of papers internationally co-authored			Percentage of papers internationally co-authored		Change*
	1997	2012	1997-2012	1997 (1)	2012 (2)	2012-1997 (%)
United States	12,498	24,604	285,056	28.1	43.2	15.1
Germany	8,185	15,041	185,189	42.3	59.6	17.4
France	6,120	11,195	140,358	43.6	61.7	18.1
United Kingdom	5,304	10,326	123,411	41.1	63.7	22.6
Italy	3,788	7,201	86,617	46.0	60.2	14.2
China	1,662	11,091	83,673	20.6	21.5	0.9
Japan	3,406	6,434	83,094	17.0	30.8	13.7
Russia	4,431	4,936	81,675	31.8	39.1	7.3
Spain	2,454	7,002	70,673	41.0	60.7	19.7
Canada	2,381	4,745	53,950	42.7	55.4	12.6
Switzerland	2,107	3,915	43,958	55.6	72.7	17.2
Poland	1,942	2,933	40,568	50.3	49.5	-0.8
Netherlands	1,763	3,230	38,895	48.2	69.5	21.2
Australia	1,349	3,798	35,149	40.1	62.4	22.3
South Korea	857	3,946	34,054	24.6	34.8	10.2
India	893	3,509	31,847	17.9	26.0	8.0
Sweden	1,477	2,608	30,987	53.5	69.9	16.4
Belgium	1,191	2,452	29,370	54.8	70.6	15.8
Brazil	988	2,207	24,903	43.8	44.2	0.4
Israel	1,132	1,644	21,873	49.5	58.0	8.6
Austria	841	1,914	20,895	56.7	73.9	17.2
Czech Republic	733	1,816	19,255	50.4	62.2	11.8
Denmark	966	1,550	16,785	62.8	71.5	8.6
Taiwan	386	1,844	16,741	17.4	32.9	15.4
Portugal	410	1,761	15,776	57.2	65.1	7.9
Finland	624	1,426	15,339	52.3	72.0	19.7
Hungary	775	1,171	15,235	55.2	69.0	13.8
Mexico	511	1,240	15,050	44.9	57.4	12.4
Greece	544	1,311	13,684	51.6	65.8	14.3
Argentina	430	1,015	11,571	41.6	59.8	18.3
Singapore	189	1,502	11,473	36.1	53.8	17.7
Chile	315	1,246	10,629	61.4	76.6	15.2
Norway	408	902	8,658	56.4	72.3	15.9
Turkey	216	1,122	8,261	28.4	37.0	8.6
Ireland	243	920	8,176	58.0	67.2	9.2
South Africa	266	960	7,016	47.2	65.8	18.6
Iran	43	1,002	5,549	20.3	20.7	0.4
New Zealand	240	516	5,312	47.1	64.9	17.8
Egypt	152	773	5,198	22.8	53.6	30.9
Saudi Arabia	52	1,261	3,997	31.0	80.6	49.6
World	33,791	66,748	793,384	19.9	26.0	6.2

* The change is calculated as the difference between column (2) and (1).

Table 3. Internationally co-authored papers by applied science field by country.

	Number of papers internationally co-authored			Percentage of papers internationally co-authored		Change*
	1997	2012	1997-2012	1997 (1)	2012 (2)	2012-1997 (%)
United States	27,921	66,579	731,617	16.9	32.4	15.5
United Kingdom	11,515	28,901	311,884	27.8	52.6	24.8
Germany	9,778	24,120	265,175	31.3	53.2	21.9
France	7,947	16,955	193,649	33.6	56.2	22.6
Canada	6,854	16,541	177,148	31.2	48.9	17.7
Japan	5,605	10,157	136,497	16.1	29.5	13.4
China	2,037	19,990	133,936	32.1	30.8	-1.3
Italy	4,735	12,496	133,066	30.8	47.1	16.3
Netherlands	4,342	11,957	116,472	35.1	57.3	22.3
Australia	3,440	12,777	113,550	26.6	50.1	23.4
Spain	2,734	11,043	96,774	27.7	48.3	20.7
Switzerland	3,474	9,116	94,026	46.5	68.3	21.8
Sweden	3,578	7,551	86,591	37.0	60.1	23.0
Belgium	2,481	6,424	67,220	45.6	65.4	19.8
Denmark	1,970	4,905	51,496	42.2	58.9	16.7
South Korea	956	6,133	50,285	30.7	28.6	-2.1
Brazil	1,307	4,852	44,598	38.7	35.7	-3.0
Austria	1,552	4,409	44,531	41.1	66.6	25.5
Russia	2,068	2,477	38,260	25.5	43.8	18.3
Finland	1,538	3,291	38,053	34.4	56.5	22.2
Israel	1,737	2,914	37,563	32.4	47.6	15.3
Norway	1,247	3,897	37,534	38.8	58.8	20.0
India	756	3,823	31,427	14.2	26.2	12.0
Poland	941	2,591	28,015	42.2	45.3	3.1
New Zealand	838	2,640	26,621	30.6	52.9	22.4
Taiwan	742	2,815	25,648	17.6	25.3	7.7
Greece	670	2,306	22,986	33.0	48.7	15.7
Mexico	695	2,075	22,835	38.6	49.0	10.4
Portugal	459	2,793	22,623	45.2	55.4	10.3
South Africa	590	2,392	21,788	27.8	58.6	30.7
Singapore	316	2,857	20,562	30.2	62.8	32.6
Czech Republic	734	1,974	20,190	45.6	53.8	8.2
Ireland	515	2,113	19,056	38.8	57.6	18.7
Argentina	563	1,768	18,722	29.0	44.7	15.7
Hungary	744	1,477	18,405	52.5	60.5	7.9
Turkey	384	1,875	17,561	19.4	25.6	6.2
Chile	303	1,327	11,780	37.4	61.0	23.7
Iran	93	1,632	10,089	40.8	28.2	-12.6
Egypt	320	1,365	9,984	38.3	56.9	18.6
Saudi Arabia	173	1,787	6,630	27.6	79.9	52.3
World	57,076	145,093	1,544,974	13.9	24.4	10.5

* The change is calculated as the difference between column (2) and (1).

Table 4. Internationally co-authored papers by basic and applied science research field.

	Number of papers internationally co-authored			Percentage of papers internationally co-authored		Change
	1997	2012	1997-2012	1997 (1)	2012 (2)	2012-1997 (%)
Basic fields	*33,791*	*66,748*	*793,384*	*19.9*	*26.0*	*6.2*
Astronomy	2,757	6,369	69,050	39.6	56.4	16.8
Chemistry	9,650	23,368	247,646	13.7	20.2	6.5
Mathematics	2,079	5,712	66,939	21.3	30.4	9.1
Physics	19,305	31,299	409,749	23.3	28.2	4.9
Applied fields	*57,076*	*145,093*	*1,544,974*	*13.9*	*24.4*	*10.5*
Biological sc.	23,504	45,470	550,070	16.7	27.4	10.7
Medical sc.	16,861	41,002	451,217	11.7	22.2	10.5
Engineering	5,650	20,106	190,073	13.2	21.7	8.6
Geosciences	5,541	16,643	168,066	20.1	33.7	13.6
Social sc.	1,752	7,570	58,618	8.7	19.5	10.7
Agricultural sc.	1,533	4,505	46,610	12.6	23.3	10.7
Psychology	1,194	5,085	41,849	8.3	20.6	12.3
Computer sc.	819	2,959	25,921	18.6	30.9	12.3
Other life sc.	222	1,753	12,550	4.5	16.8	12.3
All fields	*90,867*	*211,841*	*2,338,358*	*15.6*	*24.9*	*9.2*

* The change is calculated as the difference between column (2) and (1).

Table 5. Results of the convergence club classification for all scientific fields.

		t Statistic	β	Average Articles per capita 2012
1st club	Denmark, Sweden, Norway, Netherlands, Finland, Singapore, Belgium, Austria, Australia, New Zealand, Ireland	4.4363	0.2925	857.25
2nd club	United Kingdom, Canada, Israel, Germany, Portugal, France, Spain, Czech Republic, Greece	1.8576	0.2289	469.68
3rd club	Hungary, South Korea, Taiwan, Chile, Poland, Japan	1.4905	0.0897	181.88
4th club	Saudi Arabia, Argentina, South Africa, Russia, Turkey, Brazil, Iran, Mexico, Egypt, China, India	-0.6580	-0.0808	43.3
Divergents	Switzerland, Italy, United States			

Table 6. Results of the convergence clubs classification for basic science field.

	Countries	t Statistic	Coefficient	Average Articles per capita 2012
1st club	Switzerland, Singapore, Finland, Ireland	0.3597	0.0366	309.07
2nd club	Denmark, Sweden, Austria, Belgium, Portugal	0.5329	0.0430	233.21
3rd club	Israel, Netherlands, Germany, Norway, Czech Republic, France, Australia, United Kingdom, Spain, Canada, Italy, Greece, New Zealand	2.7582	0.3314	160.21
4th club	Hungary, Taiwan, South Korea, United States, Poland, Chile, Japan, Saudi Arabia, Iran	-0.0845	-0.0120	67.78
5st club	Russia, Argentina, South Africa, Turkey, Brazil, Mexico, Egypt, China, India	-0.1313	-0.0259	14.76

Basic science field: Astronomy, chemistry, mathematics, and physics.

Table 7. Results of the convergence clubs classification for applied science field.

	Countries	t Statistic	Coefficient	Average Articles per capita 2012
1st club	Denmark, Sweden, Norway, Netherlands, New Zealand, Australia, Singapore	3.9237	0.2031	694.16
2nd club	Finland, Belgium, Austria, Canada, Ireland, United Kingdom	2.9828	0.5039	516.42
3rd club	Israel, Germany, Portugal, France, Spain, United States, Italy, Greece, Czech Republic, Hungary, South Korea, Taiwan, Chile	1.3238	0.1067	208.86
4th club	Japan, Poland, Saudi Arabia, South Africa, Turkey, Brazil, Iran, Russia, Mexico, Egypt, China	-0.9070	-0.1360	35.43
Divergents	Switzerland, Argentina, India			

Applied science field: Biological science, medical science, engineering, geoscience, social sciences, agricultural science, psychology, computer science, and other life sciences.

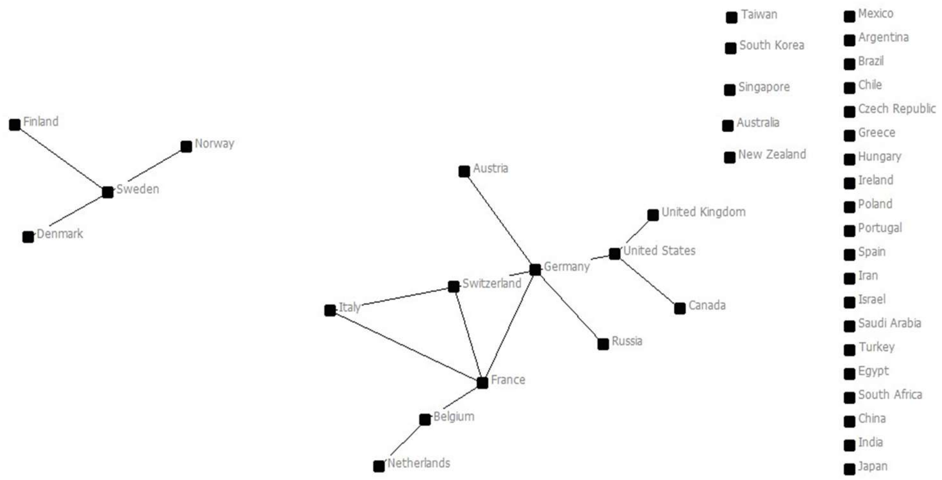


Figure 1a. International collaboration network in 1997.

Source: Own elaboration.

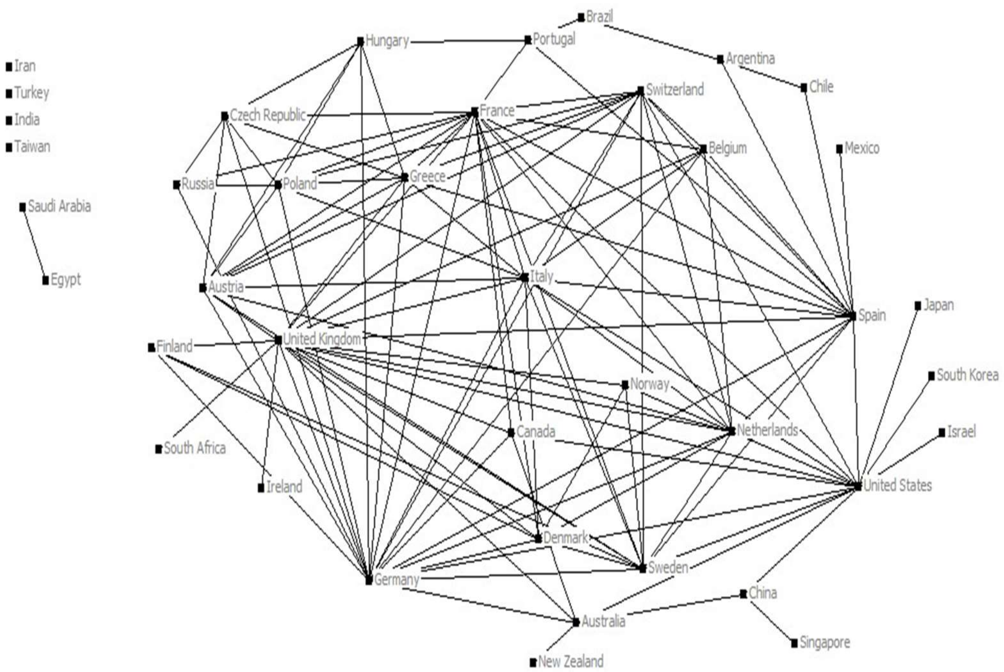


Figure 1b. International collaboration network in 2012.

Source: Own elaboration.

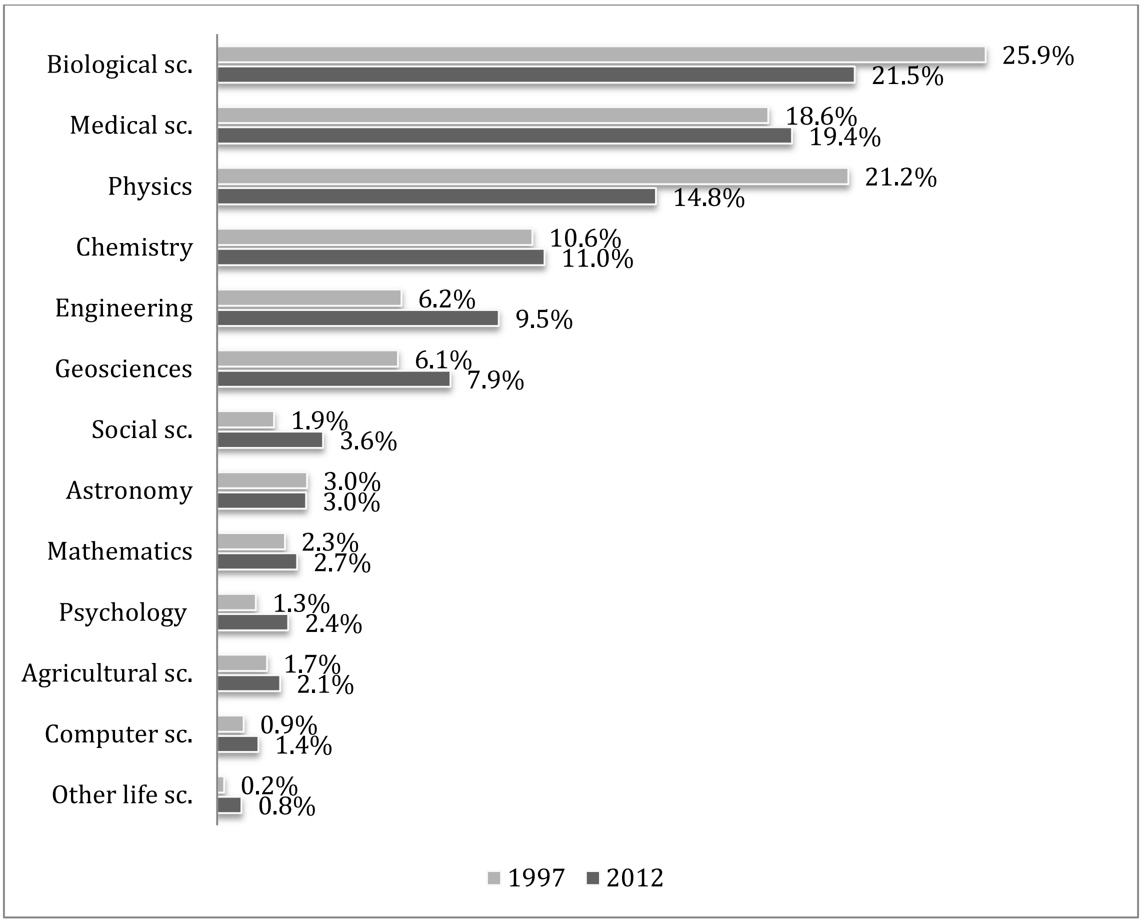
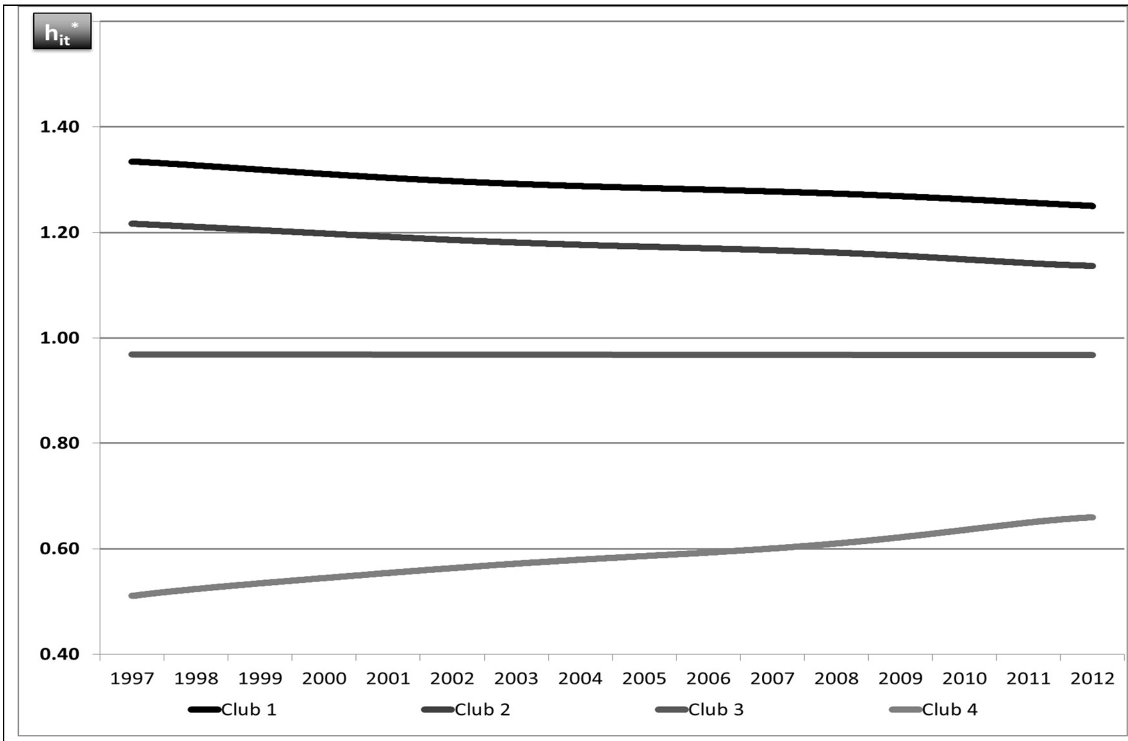


Figure 2. Distribution of internationally co-authored papers by research field.

Source: Own elaboration.



Club 1: Denmark, Sweden, Norway, Netherlands, Finland, Singapore, Belgium, Austria, Australia, New Zealand and Ireland

Club 2: United Kingdom, Canada, Israel, Germany, Portugal, France, Spain, Czech Republic and Greece

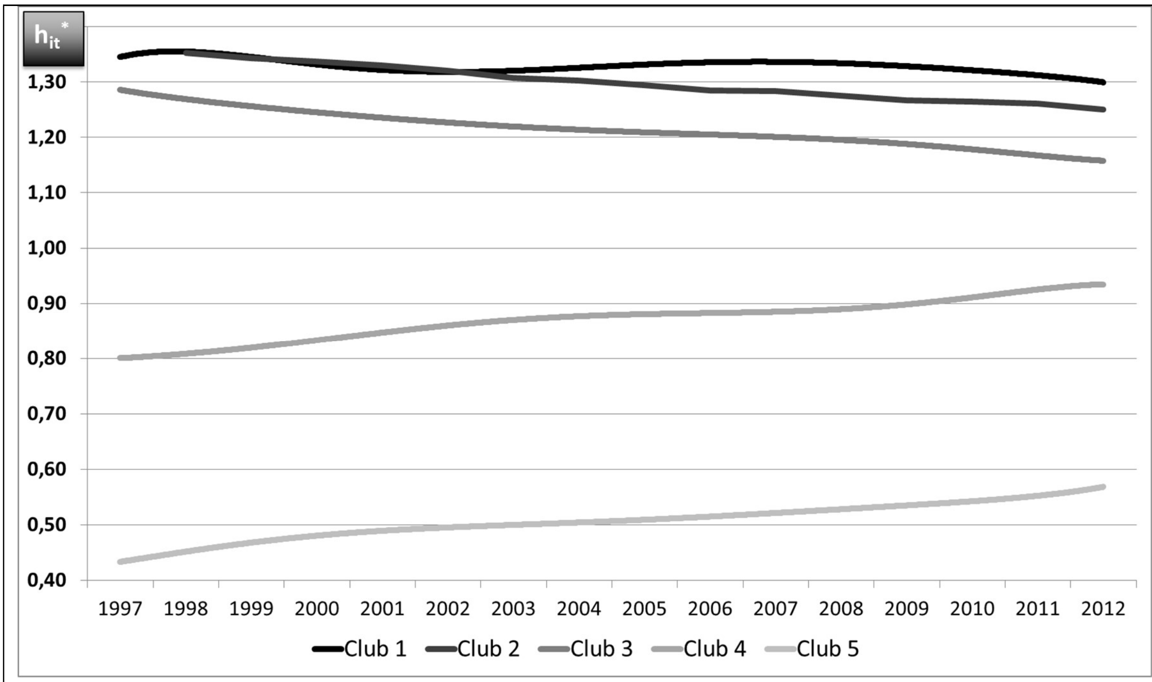
Club 3: Hungary, South Korea, Taiwan, Chile, Poland and Japan

Club 4: Saudi Arabia, Argentina, South Africa, Russia, Turkey, Brazil, Iran, Mexico, Egypt, China and India

*hit measures the transition path of each club through equation (4) (y axis).

Figure 3. Relative transition paths for all science fields.

Source: US National Science Foundation dataset (NSF, 2014) and own elaboration.



Club 1: Switzerland, Singapore, Finland, Ireland

Club 2: Denmark, Sweden, Austria, Belgium, Portugal

Club 3: Israel, Netherlands, Germany, Norway, Czech Republic, France, Australia, United Kingdom, Spain, Canada, Italy, Greece, New Zealand

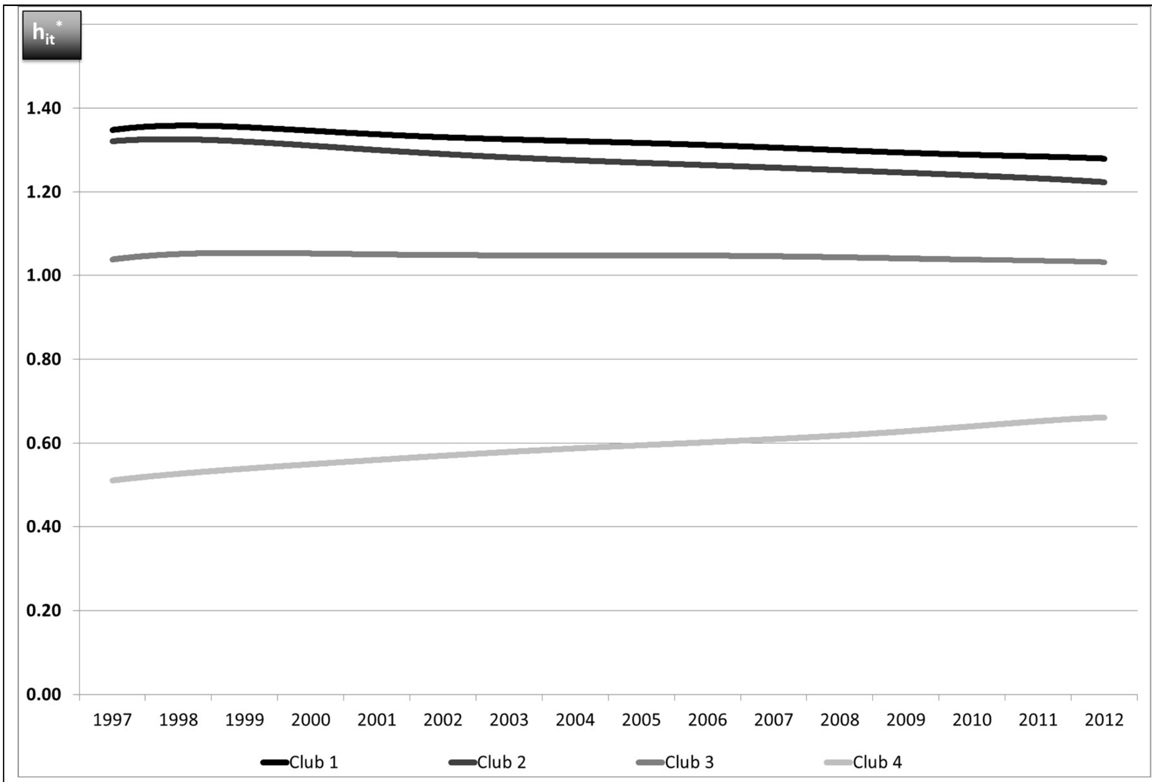
Club 4: Hungary, Taiwan, South Korea, United States, Poland, Chile, Japan, Saudi Arabia, Iran

Club 5: Russia, Argentina, South Africa, Turkey, Brazil, Mexico, Egypt, China, India

*h_{it} measures the transition path of each club through equation (4) (y axis).

Figure 4. Relative transition paths for basic fields.

Source: US National Science Foundation dataset (NSF, 2014) and own elaboration.



Club 1: Denmark, Sweden, Norway, Netherlands, New Zealand, Australia and Singapore

Club 2: Finland, Belgium, Austria, Canada, Ireland and United Kingdom

Club 3: Israel, Germany, Portugal, France, Spain, United States, Italy, Greece, Czech Republic, Hungary, South Korea, Taiwan and Chile

Club 4: Japan, Poland, Saudi Arabia, South Africa, Turkey, Brazil, Iran, Russia, Mexico, Egypt and China

*h_{it} measures the transition path of each club through equation (4) (y axis).

Figure 5. Relative transition paths for applied fields

Source: US National Science Foundation dataset (NSF, 2014) and own elaboration.