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The long-term dynamics of co-authorship scientific networks: Iberoamerican countries (1973–2010)☆

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ABSTRACT

We analyse the national production of academic knowledge in all Iberoamerican and Caribbean countries between 1973 and 2010. We show that the total number of citable scientific publications listed in the Science Citation Index (SCI), the Social Science Citation Index (SSCI) and Arts and Humanities Citation Index (A&HCI) follow an exponential growth, the same as their national productivity (number of publications per capita). During the last 38 years, Portugal shows the highest growth rate in both indicators. We explore the temporal evolution of the co-authorship patterns within a sample of 12 Iberoamerican countries (responsible for 98% of the total regional publications between 1973 and 2010) with a group of 46 other different nations. We show that the scientific co-authorship among countries follows a power-law and behaves as a self-organizing scale-free network, where each country appears as a node and each co-publication as a link. We develop a mathematical model to study the temporal evolution of co-authorship networks, based on a preferential attachment strategy and we show that the number of co-publications among countries grows quadraticly against time. We empirically determine the quadratic growth constants for 352 different co-authorship networks within the period 1973–2006. We corroborate that the connectivity of Iberoamerican countries with larger scientific networks (hubs) is growing faster than that of other less connected countries. We determine the dates, t_0, at which the co-authorship connectivities trigger the self-organizing scale-free network for each of the 352 cases. We find that the latter follows a normal distribution around year 1981.4 ± 2.2 and we connect this effect with a brain-drain process generated during the previous decade. We show how the number of co-publications $P_k^i(t)$ between country k and country i, against the coupling growth-coefficients a_k^i, follows a power-law mathematical relation. We develop a methodology to use the empirically determined growth constants for each co-authorship network to predict changes in the relative intensity of cooperation among countries and we test its predictions for the period 2007–2010. We finally discuss the implications of our findings on the science and technology policies.

1. Introduction

The application of bibliometric indicators to estimate the characteristics of international scientific cooperation patterns have been explored by diverse authors (i.e. Davison Frame et al., 1977; Beaver and Rosen, 1978; Schubert and Braun, 1990; Katz and Martin, 1997; Beaver, 2001, 2004; Glänzel and Schubert, 2004; Holmgren and Schnitzer, 2004; Wagner and Leydesdorff, 2005b). Few studies employed them to analyse the cooperation profiles among Latin American countries (Fernández et al., 1998; Narvaes-Berthelemot, 1995; Russell, 1995; De Moya-Anegón and Herrero-Solana, 1999; Gómez et al., 1999; Lemarchand, 2007). Most of the previous works only considered the aggregated behaviour among short periods of time, no longer than a decade. By doing so, the information about the annual rate of change in cooperation networks is lost. Consequently, no conclusions can be made about the results obtained by the application of different science and technology (S&T) international cooperation policies or the absence of them. The last might eventually be empirically quantified by contrasting the evolution of international cooperative agreements among institutions and countries against several S&T output indicators (Lemarchand, 2005, 2010). Unfortunately, this work was not carried out yet due to the lack of information about which international treaties and agreements are in operation among different countries.

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Besides the existence of several formal international cooperation instruments, there is no doubt that the informal instruments, among individual scientists of different countries and disciplines, may explain the co-authorship of scientific articles published in mainstream journals.

In this work, we determine the long-term evolution of the cooperation networks among 12 Iberoamerican and Caribbean countries[2] and other 46 regional and extra-regional nations. The selected countries are responsible for the 98% of the total citable scientific publications written by scientists of this region that were listed at the Science Citation Index Extended (SCI), Social Science Citation Index (SSCI) and Arts and Humanities Citation Index (A&HCI), between 1973 and 2010 (38 years)[3]. We study the bilateral co-authorship of citable articles between each of the 12 countries with the 22 most productive Iberoamerican and Caribbean countries; 19 OECD countries not included in the first group and with China, India, Israel and USSR/Russia (see Table 2).

The analysis of the aggregated temporal evolution of SCI, SSCI and A&HCI shows a homogeneous trend that is independent of any academic discipline and also avoids any substantial change in the national trends, due to the continuous incorporation of new journals to the databases. In this way, we focus our study on a cooperation network analysis within regional and extra-regional countries. Obviously, the publication in main-stream journals (listed by SCI, SSCI and A&HCI) represents only a fraction of all the cooperative research and development (R&D) activities that is taking place within the countries of our sample. The main advantage of using these databases is that they were systematically collected and organized over several decades with similar methodologies, allowing us to perform a long-term analysis with relative good confidence.

In Section 2 we analyse the long-term evolution in the production of citable scientific publications for all the countries of the region between 1973 and 2010, as well as their growth rates, productivities and regional distributions. In Section 3 we describe the methodology used to analyse the co-authorship patterns among a sample of 12 Iberoamerican countries and other 46 different nations between 1973 and 2010, and we present the main results. We study the co-authorship patterns in terms of intra and extra regional cooperation. We show that the intra-regional cooperation has been increasing smoothly during the last decades.

In Section 4 we develop a simple mathematical model of social networks applied to the study of the temporal evolution of co-authorship among countries. The model predicts a quadratic growth of co-publications (links) against time, among different countries (nodes). We show that this type of networks behaves with a self-organizing dynamics and we derive the conditions from which this process is triggered. In Section 5 we empirically analyse 352 different scientific co-authorship networks between 1973 and 2006 and we estimate the values of their growth constants, the dates at which the self-organizing dynamics starts and the correlation coefficients between the mathematical model and the real data. We determine the number of co-publications against the values of different growth coupling constants scales with a power-law.

In Section 6, we use our mathematical model and the empirically determined growth constants, to deduce a methodology to predict the near-future behaviour of the co-authorship patterns among the 352 collaborating networks. We contrast their projections with empirical data between 2007 and 2010, showing their usefulness to foresight studies. Finally, in Section 7, we present a summary with the main results of this research and their implications on the regional science and technology policies.

2. Iberoamerican mainstream knowledge production (1973–2010): The database

Within the most scientific productive 147 countries in all fields[4], covering a ten-year plus eight-month period (January 2000–August 31, 2010), the Iberoamerican countries included among the top twenty were Spain (rank 9) and Brazil (rank 15). Within the same period, our analysis shows that Mexico has the rank 28, Portugal the rank 34 and Argentina the rank 35. This is an interesting improvement[5] if we take into account that a similar survey made between 1967 and 1973 had Argentina (rank 27), Spain (rank 29), Brazil (rank 32), and Mexico (rank 34) as the most productive nations of the Iberoamerican and Caribbean region (De Solla Price, 1986: pp. 192–193).

In order to understand the process that took place between these two extremes, we analyse the temporal evolution in the production of mainstream scientific and academic knowledge in all fields. Our analyses cover the period from 1973 to 2010.

To study the distribution of published articles for each Iberoamerican and Caribbean country listed in SCI, SSCI and A&HC, we use Thomson-Reuters' Web-of-Science (WoS)[6] as our information source. We think that these databases constitute a good and qualified indicator to inquire about knowledge-production patterns within the region. The 1973–2006 data was downloaded on April 2007, while the 2007–2010 data was downloaded on April 2011. Due to some delays in the publication of several journals and delays in the WoS data-entry process, there is approximately 10–12% underestimation in the total number of published articles for the year 2010.

In this article we focus our study only in the production of citable scientific articles in all fields of knowledge. Over the years, several scholars debated about the underrepresentation of journals published in Developing Countries at SCI, SSCI and A&HCI (Gaillard, 1991; Gibbs, 1995) and in particular the Latin American and Caribbean ones (Burgos, 1995). Not all the scientists of the region under study submit their research results to mainstream journals (included at SCI, SSCI and A&HCI). Therefore, the existence of domestic journals in several countries may reflect some peculiar domestic circumstances or specific scientific national agendas that are not considered by the mainstream journals. On the other hand, some studies show that Latin American scientific journals do not have the minimum level of bibliographic control necessary to be uniquely identified, read and subscribed to, by an international audience (Cano, 1995). In this context, it is considered that periodical publications from such an infrastructure are condemned to a ghost-like existence, whereas the academics that publish in them will have their research results unrecognized. For these reasons,

[2] The countries included here within the Iberoamerican and Caribbean region are: Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Plurinational State of Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Panama, Paraguay, Peru, Portugal, Spain, St. Kitts and Nevis, St. Lucia, St. Thomas, St. Vincent and the Grenadines, Suriname, Trinidad and Tobago, Turks and Caicos, Uruguay and Bolivarian Rep. of Venezuela. All the previous countries were taken into account to estimate the total number of regional publications per year (1973–2010). Here we have excluded Puerto Rico, because it is an associate State to the USA. Most of the small Caribbean islands have practically no mainstream scientific publications at all during this period.

[3] We tried to extend the search back to 1966, but according to the information provided by the technical support of Thomson-Reuters (MD-165137) on February 2007, the complete entries for authors, addresses and countries at the WoS, were only available for the SSCI since 1966, for SCI Expanded since 1973 and for A&HCI since 1975.

[4] http://sciencewatch.com/dr/cou/2010/10decALL/

[5] Within this period, Argentina showed the opposite behaviour by having a drop from rank 27 to rank 35.

[6] http://scientific.thomson.com/products/wos/

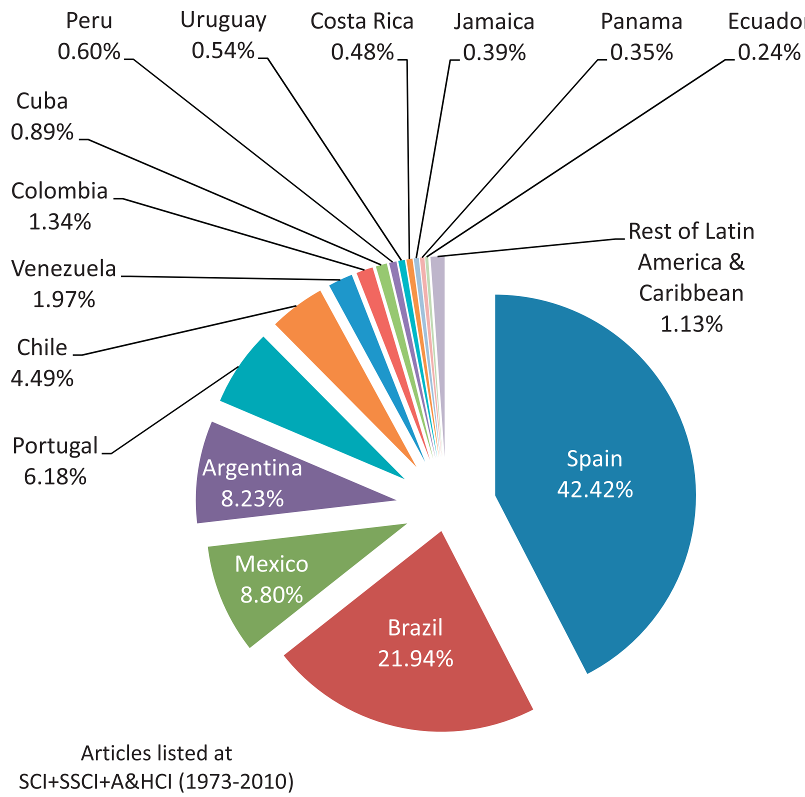

Fig. 1. Share distribution of mainstream scientific publications listed in the Science Citation Index (1973–2010), Social Science Citation Index (1973–2010) and Arts and Humanities Citation Index (1975–2010) for the Iberoamerican and Caribbean region. Here we represent those countries with more than 0.24% of the total share. To estimate the total number of Iberoamerican and Caribbean regional publications we considered the following countries: Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Plurinational State of Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guiana, Grenada, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Panama, Paraguay, Peru, Portugal, Spain, St. Kitts and Nevis, St. Lucia, St. Thomas, St. Vincent and the Grenadines, Suriname, Trinidad and Tobago, Turks and Caicos, Uruguay and Bolivarian Rep. of Venezuela. He we have excluded Puerto Rico, because it is an associate State to the USA.

during the last decades, there has been an important increase in the submission of scientific articles, written by Iberoamerican and Caribbean authors, to mainstream journals.

In spite of these reluctant points of view[7] about the under-representation of local and regional journals, we argue that there is a good correspondence among SCI, SSCI, A&HCI and other international databases of scientific knowledge production. De Moya-Anegón and Herrero-Solana (1999) showed a strong correlation in the distribution of citable articles, for those written by Latin American authors, between the Science Citation Index Extended and other databases like PASCAL, INSPEC, COMPENDEX, CHEMICAL ABSTRACTS, BIOSIS, MEDLINE and CAB. They have obtained the following values for the correlation coefficient among the different databases: $0.957 \leq R \leq 0.997$. This fact supports our hypothesis that the combination of SCI, SSCI and A&HCI might still be a good indicator for the study of mainstream scientific knowledge-production and the evolution of co-authorship networks among different countries.

Fig. 1 shows the distribution of published articles at the three databases, between 1973 and 2010, per country as a percentage of the total number of articles published in all the Iberoamerican and Caribbean countries during the same period. Clearly, the European countries of our sample (Spain and Portugal) account for almost 50% of all the publications. This implies that if we want to calculate the shares of publications among Latin American and Caribbean countries alone, a rough estimation can be obtained by multiplying the values of Fig. 1 by a factor of 2.

Fig. 2 shows the total number of published articles at the three databases per year, between 1973 and 2010, in a log-linear scale for the 12 Iberoamerican nations with the highest number of mainstream scientific publications. The distribution of total number of publications per year, in most of the countries, follows an exponential growth behaviour which can be described by $P_k(t) = \varphi e^{\gamma t}$, where $P_k(t)$ is the total number of publications of country k at time t, while φ and γ are empirically determined constants.

Table 1 shows the 18 most productive Iberoamerican and Caribbean countries in terms of scientific publications listed at SCI, SSCI and A&HCI between 1973 and 2010. It also represent the exponential growth rates and their corresponding fitting correlation coefficients ($R\gamma\varepsilon\delta$) to measure: (1) the growth in the number of citable publication against time (γ and R_γ); (2) the growth in the number of citable publications per million inhabitants against time (ε and $R\varepsilon$); and (3) the growth in the number of citable publications per GDP in 2005 constant US billion dollars (δ and R_δ) against time. The following columns represent the different country rakings ordered by the total number of articles (1973–2010), and the values of the exponential growth constants γ, ε and δ respectively. The population and GDP data used for these computations, for each country and each different year between 1973 and 2010, were taken from the UN Statistics Division (http://unstats.un.org/).

[7] In the last years, new regional databases were created to account the publications in Iberoamerican journals, not usually listed in SCI, SSCI or A&HCI. Some examples are PERIODICA (≈1400 science and technology journals published in Latin America and the Caribbean); CLASE (≈1200 social sciences journals published in Latin America and the Caribbean); LILACS (Medicine and Health Sciences journals published in Latin America and the Caribbean); ICYT (≈550 science and technology journals published in Spain); and IME (≈115 Medicine and Health Sciences journals published in Spain). LATINDEX is also another interesting initiative to evaluate the endogenous Iberoamerican scientific production.

Table 1
Iberoamerican Countries with the highest number scientific publications at mainstream journals between 1973 and 2010.

Country	γ	R_γ	ε	R_ε	δ	R_δ	#	Country	Total number of articles 1973–2010	#	Country	γ	#	Country	ε	#	Country	δ
Argentina	0.0541	0.972	0.041	0.901	0.0349	0.928	1	Spain	703,031	1	Portugal	0.1250	1	Portugal	0.1215	1	Portugal	0.0973
Bolivia	0.0760	0.940	0.055	0.805	0.0525	0.904	2	Brazil	363,581	2	Colombia	0.1104	2	Colombia	0.0925	2	Cuba	0.0723
Brazil	0.0952	0.990	0.078	0.967	0.0670	0.981	3	Mexico	145,800	3	Spain	0.0983	3	Spain	0.0918	3	Spain	0.0718
Chile	0.0573	0.946	0.043	0.817	0.0084	0.315	4	Argentina	136,369	4	Brazil	0.0952	4	Cuba	0.0809	4	Brazil	0.0670
Colombia	0.1104	0.928	0.093	0.812	0.0547	0.893	5	Portugal	102,444	5	Ecuador	0.0901	5	Uruguay	0.0794	5	Ecuador	0.0661
Costa Rica	0.0516	0.963	0.027	0.781	0.0112	0.562	6	Chile	74,470	6	Cuba	0.0867	6	Brazil	0.0776	6	Uruguay	0.0624
Cuba	0.0867	0.962	0.081	0.920	0.0723	0.941	7	Venezuela	32,679	7	Uruguay	0.0837	7	Ecuador	0.0740	7	Colombia	0.0547
Ecuador	0.0901	0.979	0.074	0.927	0.0661	0.950	8	Colombia	22,207	8	Mexico	0.0788	8	Trinidad & Tobago	0.0656	8	Bolivia	0.0525
Guatemala	0.0203	0.694	−0.004	0.033	−0.0110	0.483	9	Cuba	14,817	9	Bolivia	0.0760	9	Mexico	0.0608	9	Mexico	0.0503
Jamaica	0.0128	0.712	0.004	0.110	−0.0020	0.089	10	Peru	9,897	10	Chile	0.0573	10	Bolivia	0.0554	10	Trinidad & Tobago	0.0456
Mexico	0.0788	0.991	0.061	0.962	0.0503	0.973	11	Uruguay	8,915	11	Peru	0.0568	11	Chile	0.0426	11	Argentina	0.0349
Panama	0.0419	0.958	0.023	0.757	0.0004	0.035	12	Costa Rica	8,011	12	Argentina	0.0541	12	Argentina	0.0408	12	Peru	0.0337
Peru	0.0568	0.938	0.377	0.727	0.0337	0.896	13	Jamaica	6,512	13	Costa Rica	0.0516	13	Peru	0.0377	13	Venezuela	0.0179
Portugal	0.1250	0.997	0.122	0.994	0.0973	0.994	14	Panama	5,820	14	Trinidad & Tobago	0.0420	14	Costa Rica	0.0272	14	Costa Rica	0.0112
Spain	0.0983	0.979	0.092	0.951	0.0718	0.951	15	Ecuador	3,903	15	Panama	0.0419	15	Panama	0.0226	15	Chile	0.0084
Trinidad & Tobago	0.0420	0.917	0.656	0.595	0.0456	0.582	16	Trinidad & Tobago	3,815	16	Venezuela	0.0420	16	Venezuela	0.0140	16	Panama	0.0004
Uruguay	0.0837	0.966	0.079	0.925	0.0624	0.940	17	Bolivia	2,806	17	Guatemala	0.0760	17	Jamaica	0.0043	17	Jamaica	−0.0020
Venezuela	0.0362	0.862	0.014	0.283	0.0179	0.633	18	Guatemala	2,769	18	Jamaica	0.0203	18	Guatemala	−0.0040	18	Guatemala	−0.0110

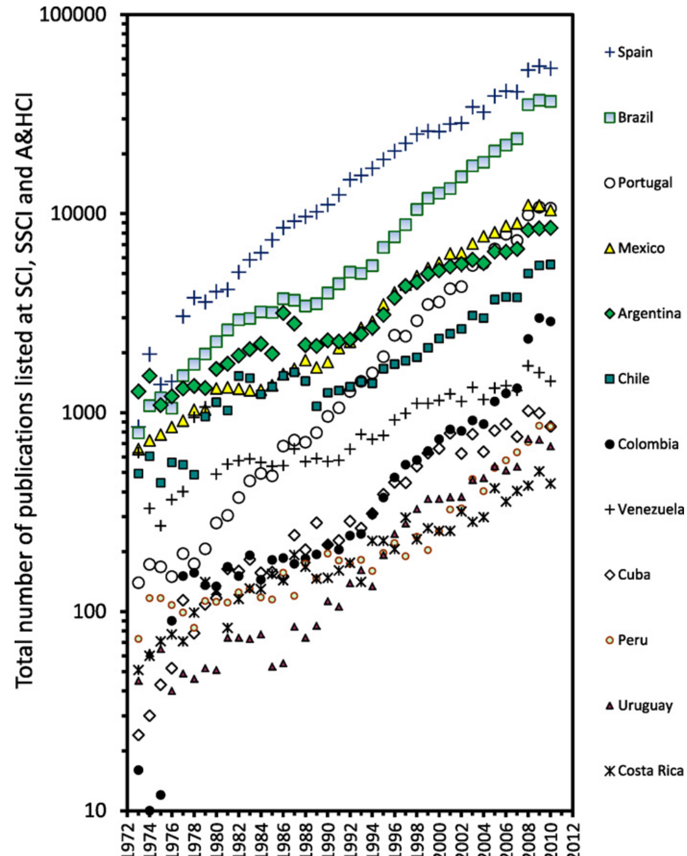

Fig. 2. Publication of peer-review articles listed in SCI, SSCI and A&HCI of the 12 most productive Iberoamerican and Caribbean countries (1973–2010). They approximately follow exponential growths. During this period, Portugal shows the highest growth rate.

It is very interesting to observe the difference between the total number publications and the exponential growth constant size rakings. Portugal has the highest γ, ε and δ growth-constants of our sample. In these three cases they show exponential growths with fitting correlation-constants $R_{\gamma,\varepsilon,\delta} > 0.99$. Within a period of 38 years, Portugal multiplied its publications by a factor of 76; its publications per million people by a factor of 64 and its publications per GDP in constant 2005 USD by a factor of 34. In 1973 Portugal had the 7th position within the raking of publications in the region (close to Peru and Jamaica) in the number of published articles of the region, while in 2010 moved to the 3rd one shared with Mexico which has 10 times Portugal's population.

Another very interesting case is Colombia, which has the second highest γ and ε constants with even higher growth constants if we consider only the data after 1993. This is consistent with several S&T organizational reforms generated in 1990, such as the creation of the National Science and Technology System and the inclusion of COLCIENCIAS as part of the National Department of Planning (Garay et al., 1998). Spain has the third ranking place at the three exponential growth processes (γ, ε, and δ).

On the other hand, Venezuela, Guatemala and Jamaica have the lowest γ, ε, and δ constant rates. In the last cases, the number of citable publications per million people have increased less than a factor of 2 over 38 years.

These bibliometric measurements belong to the S&T output indicators set (i.e. OECD Frascati Manual), and their study represents, in many ways, the performance of the national production of knowledge as a consequence of their R&D activities. The absence of growth, for almost four decades (i.e. Venezuela and Jamaica) implies a failure of the applied S&T policies in those countries. On the contrary, the S&T policies applied in Spain, Brazil and Portugal show a relative good success, as shown by the temporal evolution of most of their main S&T indicators, such as S&T Funding, number of researchers, new PhDs, number of scientific publications, etc. (Lemarchand, 2010).

At this point, it is important to take into account that during the analysed period, the number of journals and consequently the total number of published articles included within the WoS' database was substantially expanded. Mabe (2003) showed that journal growth rates have been remarkably consistent over time with average rates of 0.034 since 1800 to the present day. This study presents evidences, that during the whole XX Century, this growth phenomena appear to show a system that is self-organising and in equilibrium with a 0.032 growth constant. Considering that WoS' database only includes a small fraction of all the new journals that are published, the database growth rate would be even smaller than the one estimated by Mabe (2003). A quick look to the values of the γ-growth constants presented at Table 1 clearly shows that $\gamma \gg 0.032$ (with the exception of Jamaica). Consequently, the productivity of scientific articles, published by the countries of our sample during the last 38 years, still behaves with an exponential growth ($\gamma - 0.032 > 0$).

Mabe had also analysed the high coincidence between journal growth rates and world scientists' growth-rates over the last 50 years ($\gamma_{scie} \approx 0.03$). According to this study, the phenomenon that is causing the journal growth is the rise in the number of scientists. The last hypothesis is consistent with the results of Table 1, and with the fact that during the last decades the growth rates for the number of scientists in Latin America had values that were over the world's average growth (Lemarchand, 2010: p. 56). The rates for Spain and Portugal were even higher.

Another way to study the long-term behaviour of mainstream scientific publications can be performed by analysing the evolution of the societal knowledge productivity, in terms of number of publications per million inhabitants against time. In Fig. 3 we show, in log-linear scale, the yearly distribution of publications at SCI, SSCI and A&HCI per million inhabitants, for the 12 most productive nations of the region. Both European countries (Spain and Portugal) show a clear exponential growth, in which Spain increased 47 times its productivity over a 38-year period, while Portugal 64 times. By keeping the same growth rates, Portugal may well reach Spain's productivity in the next years. In Latin America, Cuba and Brazil showed the most important growths, increasing their productivities with factors of 29 and 24 respectively. Another interesting case is Grenada, a small Caribbean island that produces a small number of citable articles per year. During the last 18 years, Grenada increased the number of publications in mainstream journals per million people in a factor of 68.

A careful look at the Fig. 3 will also show that for most of Latin American countries of the sample, between the late 1970s and the late 1980s, their productivity remained almost constant. Lemarchand (2010: pp. 100–120) introduced a detailed study of the long-term evolution of science, technology and innovation policies (STIP) applied within Latin American and the Caribbean (LAC) over 60 years, using the long-wave theory of technoeconomical paradigms shift (see Mallmann and Lemarchand, 1998). He presents empirical evidences that show how that particular period was related with a societal phase (1974–1987) at which social actors were *questioning* the previous technoeconomical paradigm. This was followed by another phase (1988–2001) at which a new technoeconomical paradigm was *formulated*. In terms of a long-wave theory, these two phases are categorized by an antagonist societal mood (Mallmann and Lemarchand, 1998). This period was characterized by economic crises, high inflation rates, increase in the foreign debt, macroeconomic adjustments, reduction of public

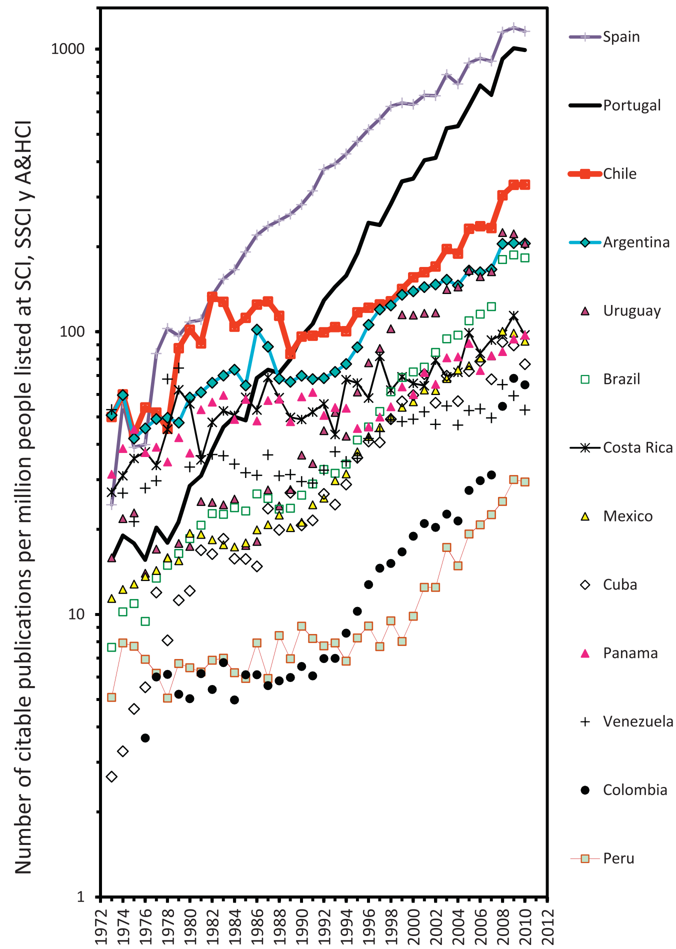

Fig. 3. Temporal evolution of total number of publications in the three databases (SCI, SSCI and A&HCI) per million inhabitants for each of the 12 Iberoamerican countries responsible for the 98% of the total number of articles published between 1973 and 2010 within the region. The population data for each year at each country were obtained at UN Statistics Division (http://unstats.un.org/).

expenditures on S&T activities, predominance of military governments (see Fig. 13), absence of academic freedom, high brain-drain rate of scientists and technicians, etc. From the mid-nineties most of the nations of the region begun increasing their productivity again.

Since the early days of scientometrics, a correlation between the total number of publications and the national GDP was suggested (De Solla Price, 1986). A recent study showed a high correlation between the number of publications over 10-year period – within the different regions of the world (Africa, Arab Countries, Asia-Pacific, Europe and North America, and Latin America and the Caribbean) – and the shares of global GDP within the same regions (Lemarchand, 2010: p. 20). Here we test this correlation analysing the number of publications over the national GDP expressed in constant 2005 USD against time (1973–2009). Table 1 shows these results. Only 61% of the sample of 18 countries analysed presents a high correlation. At this point it is not possible to generalize the hypothesis that only GDP is the driver for scientific publications.

3. Iberoamerican mainstream co-publication patterns (1973–2010)

Co-authorship is one of the most tangible and well documented forms of scientific collaboration (Glänzel and Schubert, 2004). Almost every aspect of scientific cooperative networks can be studied by analysing co-authorship patterns with the employment of bibliometric methods. For our study, we select only those nations

Table 2
Countries of our sample.

Countries analysed	Co-authorship with		
	Iberoamerican and Caribbean countries	OECD countries	Other countries
a) Argentina	1) Argentina	24) Australia	43) China
b) Brazil	2) Barbados	25) Austria	44) India
c) Chile	3) Bolivia	26) Belgium	45) Israel
d) Colombia	4) Brazil	27) Canada	46) USSR/Russia
d) Costa Rica	5) Chile	28) Denmark	
f) Cuba	6) Colombia	29) Finland	
g) Mexico	7) Costa Rica	30) France	
h) Peru	8) Cuba	31) Germany	
i) Portugal	9) Ecuador	32) Ireland	
j) Spain	10) Guatemala	33) Italy	
k) Uruguay	11) Guyana	34) Japan	
l) Venezuela	12) French Guiana	35) Netherlands	
	13) Honduras	36) Norway	
	14) Jamaica	37) Poland	
	15) Mexico	38) South Korea	
	16) Nicaragua	39) Sweden	
	17) Panama	40) Switzerland	
	18) Paraguay	41) United Kingdom	
	19) Peru	42) United States	
	20) Portugal		
	21) Spain		
	22) Uruguay		
	23) Venezuela		

with shares over 0.5% of the total regional production between 1973 and 2010 (see Fig. 1). In this way, the countries of our sample are: Spain, Brazil, Mexico, Argentina, Portugal, Chile, Venezuela, Colombia, Cuba, Peru, Uruguay and Costa Rica. This set covers the 98% of the total number of publications originated in all Iberoamerican and Caribbean nations.

We use the WoS resources to analyse the number of bilateral co-publications for each country of our sample, per year, between 1973 and 2010, with other 46 different nations taken from the list shown in Table 2. The latter includes the countries with larger number of mainstream scientific publications in the world, listed in SCI, SSCI and A&HCI.[8] The 1973–2006 data were downloaded between February and April 2007, while the 2007–2010 in April 2011.

We search for the number of citable articles per year (at the three databases) that have at least one author from the Iberoamerican country under study and another author from each of the 46 countries of our list. In this way, we got the number of bilateral co-publications that each pair of countries generates per year between 1973 and 2010. Our focus is the study of the "links between pairs of countries". For doing so, we only need to know the existence of connectivity, or not, between each Iberoamerican country and each other nation from our list (Table 2). We do not analyse how many of these bilateral co-authorship articles were really written by three or more authors from different countries. Those articles written by 3 or more authors from different countries will generate several links between "different" pairs of countries, but only one link between two specific countries. The total number of links in the whole study will be larger than the total number of papers, but the number of links between each pair of countries will exactly match the number of papers that were co-published between the same pair of countries.

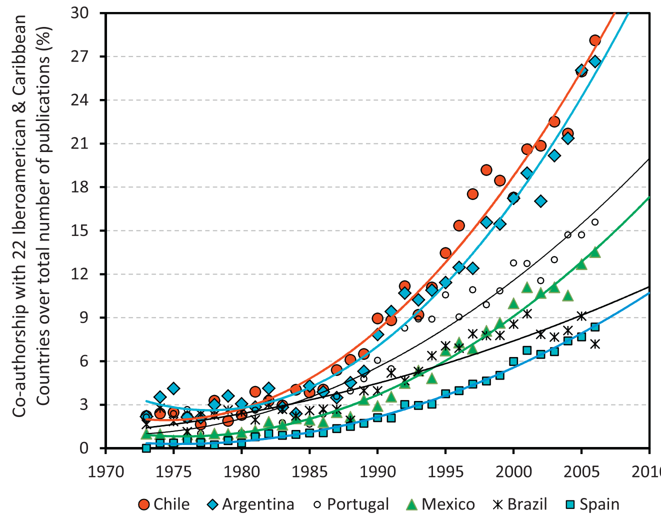

Fig. 4. Temporal evolution of the scientific co-authorship between Spain, Brazil, Mexico, Argentina, Portugal and Chile with the 22 most productive countries of the Iberoamerican and Caribbean region as a whole. The vertical axes represent the percentage of co-publications with Iberoamerican and Caribbean countries. Spain and Brazil work as real "hubs" where the rest of the regional countries concentrate most of their collaboration's shares with them, increasing in this way the internal percentage of co-authorship among Iberoamerican nations.

In a pioneering article on the size dependence of international collaboration, Schubert and Braun (1990) concluded that "no Latin American collaboration links between big regional but lonely staying powers Brazil, Argentina and Chile" were observed. That was the case in the early eighties (Lemarchand, 2010).

To check any change in the previous findings, we analyse the temporal evolution of regional scientific co-publications at mainstream journals. We have analysed the co-publication behaviour of each nation of our sample with other 22 regional countries (99.8% whole mainstream publications) as an aggregated unit. In Fig. 4 we show the internal co-publications growth among Iberoamerican countries, expressed as percentage of the aggregated number of co-publications with the any of the 22 countries of the sample over the total number of national publications in each year. A careful analysis shows that the intraregional cooperation is increasing quadratically. At this point, we cannot determine if this behaviour is a consequence of the application of regional cooperation agreements and several explicit S&T policies driven by free-trade and other regional integration treaties, or not. The number of international formal agreements has increased linearly in time over the last 40 years (Lemarchand, 2005) and there is an increasing number of initiatives towards the coordination and integration of all STI policies among the Iberoamerican countries (Lemarchand, 2010). It is also very interesting to check that the intensity of the aggregated cooperation with regional countries is inversely proportional to the size of the national scientific network (i.e. Spain is the country with the highest number of mainstream scientific articles, but the one with less regional cooperation shares). The last effect can be explained in terms of a self-organizing co-authorship scale-free network dynamics.

Albert and Barabási (2002) showed that highly connected nodes (in our case countries, i.e. USA, UK, France, Germany, etc.) increased their connectivity faster than their less connected peers. They called this effect as preferential attachment. Based on the last conceptual framework, Wagner and Leydesdorff (2005b) considered the growth of international scientific connectivities as a consequence of mechanisms of reputations and rewards, where scientists

[8] In this study: (1) the co-authorship patterns with United Kingdom (U.K.) are considered as a single unit. To estimate them, we have taken into account all those author's addresses located at England, Scotland, Wales and Northern Ireland; (2) in the case of Germany, between 1973 and 1989, we have considered as a single unit the aggregated co-publications of both: the German Democratic Republic (East Germany) and the Federal Republic of Germany (West Germany); (3) after 1992 the time series from the former USSR are followed by the Russian Federation data.

Table 3
Size distributions of Iberoamerican co-authorship networks.

Iberoamerican country	Number of larger co-authorship networks or "hubs"	Percentage of co-publications with larger networks (%)	Number of smaller co-authorship networks	Percentage of co-publications with smaller networks (%)	Traffic coefficient: (Percentage larger networks/Percentage smaller networks)
Spain	9	28.37	30	13.76	2.1
Brazil	16	32.60	24	8.77	3.7
Mexico	26	69.52	14	3.25	21.4
Argentina	27	35.50	13	3.69	9.6
Portugal	26	73.97	5	0.82	90.2
Chile	28	53.30	7	2.23	23.9
Venezuela	21	44.49	4	1.68	26.5
Colombia	22	90.84	3	3.20	28.4
Cuba	22	53.29	–	–	–
Peru	15	71.30	2	1.93	36.9
Uruguay	19	69.91	–	–	–
Costa Rica	16	66.02	3	3.34	19.8

collaborate to gain visibility, reputation, access to state-of-the-art technologies and funding.

It is interesting to check that these main co-authorship links are established with nodes (countries) that have higher R + D budgets and extensive S&T networks than the Iberoamerican country under analysis. Assuming complex network behaviour, the strategy to extend a cooperative co-authorship strategy with countries that have a more extensive scientific network is equivalent to the choice between holding a new document in a web server with high traffic (i.e. Google) or in a web-page with very few visits. In this way, scientists working on the periphery looking to increase the visibility of their research strive to link their research to the international research community, particularly through the co-publication with authors that are members of networks with larger connectivities (i.e. USA, UK, Germany, France, etc.).

From a sociological point of view, the individual scientists behave in such a way to enhance what Merton (1968, 1988) called Matthew Effect.[9] It is very interesting to observe that Merton considered that "*the Matthew Effect may serve to heighten the visibility of contributions to science by scientists of acknowledged standing and to reduce the visibility of contributions by authors who are less well known.*" He also theorized that a macrosocial version of the Matthew Effect works as a maximization principle in those processes of social selection that currently lead to the concentration of scientific resources and talent. He had implicitly identified the sociological consequences of a power-law distribution applied to the prestige, access to resources, visibility of prominent scientists and institutions, or, in our terms, to the existence of preferential attachments.

One of the most common sources for establishing new links (preferential attachment) between a periphery country (node) and a "hub" is the international mobility of scientists, technicians, scholars and graduate students. This strategy was followed by individuals from most of the Iberoamerican countries over the last 60 years (Lemarchand, 2010). The access to higher R&D budgets, better laboratories or infrastructures, and a scientific network with wider connectivity and visibility, increase the individual productivity and give the possibility to collaborate later in hot topics with scientists of their own country. In this way, they extend the visibility of their national scientific network. This mobility is favoured by international differences in earnings and technological gaps, the demand for talents from high developed countries, possibilities to work in the-state-of-the-art of the generation of new knowledge and new technologies. The last set of motivations can be considered as "pull-factors."

In turn, those "push-factors" which induce scientists, technicians, engineers and other scholars to emigrate are: low salaries at home, limited professional recognition, poor career prospects, and the absence of peer research groups at their home country (Solimano, 2008).

These highly skilled expatriate networks, through a connectionist approach, linking Diaspora members with their countries of origin, turn the brain drain into a brain gain approach (Meyer, 2001). In recent years, several empirical and theoretical studies that include the case of several Latin American countries support the last conceptions (Meyer et al., 1997; Kuznetsov and Sabel, 2006; Bassarsky, 2007; Solimano, 2008; Thorn and Holm-Nielsen, 2008).

We have empirically corroborated that the countries of the region tend to mainly cooperate with "hubs" or bigger scientific networks. The higher number of articles is co-published with larger scientific networks. Table 3 shows the distribution of hubs and other larger co-authorships networks, the distribution of smaller collaborative webs and in both cases their corresponding percentage of co-publications over the total number of articles (1973–2006) for each country of our sample.[10]

Table 3 shows the differences among the S&T cooperation strategies performed by the Iberoamerican countries of our sample. While several nations focus their co-authorship strategies on co-publications with larger networks (Colombia; Portugal, Peru, Uruguay and Mexico), others (Spain, Brazil and Argentina) share their mainstream scientific articles among local authors, hubs and smaller networks.

In Section 5 we study the characteristics of 352 different co-authorship Iberoamerican networks. The data provide in Table 3 shows that 70.2% of all the networks surveyed in Section 5 are hubs or larger co-authorship networks. We estimate that the number of co-publications generated by the last group of networks represents 39.6% of the total number of articles published by the 12 countries of our sample between 1973 and 2006. While the co-publications with smaller scientific co-authorship networks are responsible for only 8.8% of the total number of articles from these 12 nations. We noticed that Spain (which works like a real "hub" for the Iberoamerican community) is the country responsible for contributing 6.1% to the last 8.8%.

In the last column of Table 3 we represent the "traffic coefficient" or the ratio between the percentages of co-publications with

[9] The Matthew Effect took its name from the Gospel according to St. Matthew: "For unto every one that hath shall be given, and he shall have abundance: but from him that hath not shall be taken away even that which he hath." (Merton, 1968; p.58).

[10] Here, as well as in Section 5, all the computation were made for the period 1973–2006, which corresponds to the date of the first submission of this manuscript (2008). The co-authorship data between 2007 and 2010 were used here to test the theoretical predictions of our original model.

larger scientific networks over the percentages of co-publications with smaller ones. Portugal's traffic coefficient is 90.2, several times larger than any other case of our sample (i.e. Spain: 2.1; Brazil: 3.7; Mexico: 21.4; Argentina 9.6, Chile: 23.9). By concentrating 90.2 times more co-publications with more visible and larger scientific networks than with smaller ones, the S&T cooperation strategy followed by Portugal enable the country to have the highest growth rates of mainstream scientific articles production and its corresponding productivity (see Figs. 2 and 3).

4. The temporal evolution of self-organized co-authorship social networks

The study of all kind of complex networks has undergone an accelerated expansion in the last few years, after the introduction of scale-free and power-law mathematical models (Albert and Barabási, 2002; Dorogovtsevyz and Mendes, 2002; Wang, 2002; Boccaletti et al., 2006) and small-world networks (Newman, 2001), which, in turn, have induced the study of many different phenomena under these new theoretical approaches. The co-authorship network is one of them (Barabási et al., 2002; Ramasco et al., 2004; Wagner and Leydesdorff, 2005a,b; Tomassini and Luthi, 2007). Nodes in co-authorship networks are paper authors, joined by edges if they have written at least one article together.

Ramasco et al. (2004) also developed a mathematical model to show the self-organizing properties of all kind of collaboration networks. This model includes a growing network that combines preferential edge attachment with the bipartite structure and depends on the total number of collaborators (in our case countries) and acts of collaborations (in our case co-publications). According to this model, we can infer that co-authorship networks are self-organized and do not depend on any specific national S&T policy but on the internal dynamics of the scientific enterprise. Melin (2000) showed that the scientific collaborations are characterized by strong pragmatism and a high degree of self-organization. The same conclusions were treated with some detail by Wagner and Leydesdorff (2005a) suggesting that the scientific collaboration dynamics are caused by the self-interests of individual scientists, rather than by other structural, institutional or policy related factors that have been suggested previously.

Using data provided by Fernández et al. (1998) we verify that the co-authorship of Iberoamerican and Caribbean countries also behaves as a self-organizing social network. In Fig. 5, we plot in a log–log scale the number of co-publications by Latin American authors (1991–1995) listed in SCI against the number of cooperative countries (i.e. $S = 2; 3; 4; \ldots 14$). The graph shows a power-law distribution, characteristic of a scale-free network (Albert and Barabási, 2002), where the countries behave as *nodes* and the co-publications as *links*, connecting nodes. The plotted data can be fitted by the following equation $P = 187941\, S^{-4.481}$, where P is the total number of co-publications as a function of S (number of countries that participates in the co-publication). From the previous relation, it is clear that the most frequent type of co-authorship is the bilateral one, while the number of co-publications among 3; 4; ... 14 countries decays hyperbolically.

Besides the fact that several mathematical models have already been developed to understand the scientific co-authorship dynamics (Newman, 2001; Barabási et al., 2002; Ramasco et al., 2004; Li et al., 2007), hereafter we develop a formalism to analyse the temporal evolution and the long-term behaviour of co-publication networks among countries. Its simplicity will allow us to empirically determine its growth constants from available data-sets, to establish the dates at which the self-organizing network dynamics is triggered and to make some predictions about the future behaviours.

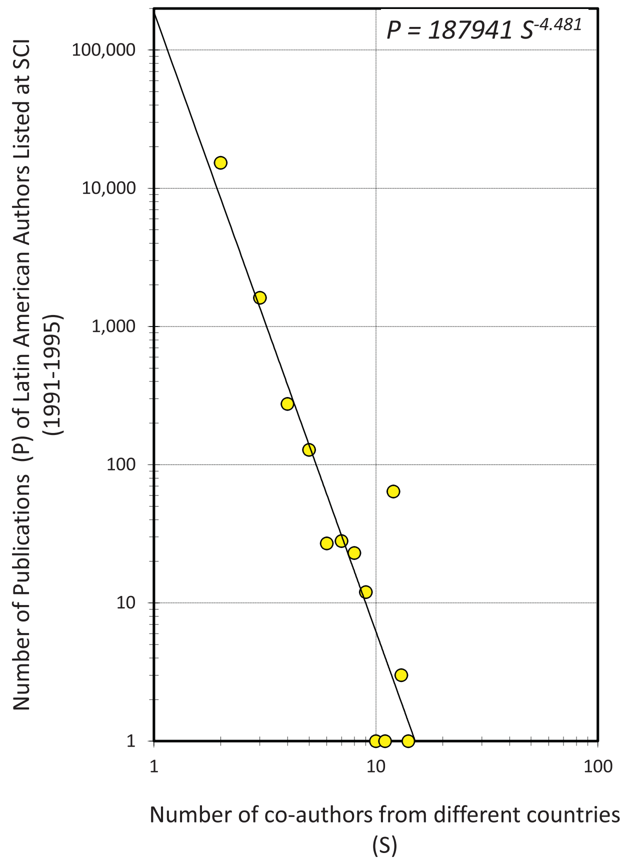

Fig. 5. Using the numerical data analysed by Fernández et al. (1998), here we represent the distribution of mainstream scientific publications (links) by Latin American authors, listed in SCI between 1991 and 1995, against the number of authors from different countries (nodes). The graph shows a power-law distribution that is characteristic of a scale-free social network dynamics.

In this work we assume that new researchers join the national scientific network (nodes) following a linear growth process describe by:

$$S(t) = \sigma t + \theta \tag{1}$$

Here $S(t)$ represents total number of nodes, σ the growth constant and θ represents the total number of nodes when $t = 0$.

We apply the continuum-theory network model developed by Barabási et al. (2002), in order to deduce the mathematical relation that describes the temporal evolution of the average number of links per node. By assuming, respectively, $K_i(t)$ as the number of links that node i have at time t and $P(t)$ as the total number of links (co-publications) at time t, we estimate the average number of links per node in the system at time t as:

$$\langle K \rangle = \frac{P(t)}{S(t)} \tag{2}$$

Following Barabási et al. (2002), here we assume that the probability to create a new internal link between two existing nodes is proportional with the product of their connectivities. By defining α as the number of newly created internal links per node in unit time, we are able to write the probability that between countries (nodes) i and j, a new scientific paper (internal link) is published as:

$$\aleph_{ij} = \frac{2\alpha S(t) K_i K_j}{\sum_{l,m} K_l K_m} \tag{3}$$

The summation in the denominator is done for all values at which $l \neq m$.

Following the original preferential attachment model developed by Barabási and Albert (1999) we assume that a node i has K_i links, so the probability that an incoming node will connect to it, is given by

$$\aleph_i = \beta \frac{K_i}{\sum_j K_j} \quad (4)$$

where β is the average number of new links that an incoming node generates. By doing so, we are able to propose the dynamical rules that govern our evolving network model, capturing the basic mechanism governing the evolution of co-authorship networks (Barabási et al., 2002): (a) Nodes join the network at a constant rate; (b) Incoming nodes link to the already present nodes following preferential attachment; (c) Nodes already present in the network form new internal links following preferential attachment.

From (1) we know that new links join the system with a constant rate, $dS(t)/dt = \sigma$, the continuum equation that represents the behaviour of the temporal evolution of the number of co-publications (links), associated with country (node) i, is the following master equation (Barabási et al., 2002):

$$\frac{dK_i}{dt} = \sigma\beta \frac{K_i}{\sum_j K_j} + 2\alpha S(t) \sum_j \frac{K_i K_j}{\sum_{l,m} K_l K_m} \quad (5)$$

In the last equation, the first term on the right-hand side describes the contribution due to new nodes (4) and the second term gives the new links created with already existing nodes (3). The total number of links at time t can be computed taking into account the internal and external preferential attachment rules (Barabási et al., 2002):

$$\sum_i K_i = \int_0^t 2[S(t')\alpha + \sigma\beta]dt' = t\sigma(\alpha t + 2\beta) \quad (6)$$

Consequently, the average number of links per node increases linearly in time as:

$$\langle K \rangle = \alpha t + 2\beta \quad (7)$$

Combining Eqs. (1), (2) and (7) we obtain:

$$P(t) = \langle K \rangle S(t) = (\alpha t + 2\beta)(\sigma t + \theta) \quad \text{or}$$
$$P(t) = \alpha\sigma t^2 + (\alpha\theta + 2\beta\sigma)t + 2\beta\theta \quad (8)$$

Eq. (8) clearly shows the quadratic dependence of the number of co-publications between country i and j, against time. This is a new result that was not predicted by Barabási et al. (2002) model which assumed $\theta = 0$.

By introducing a change of variables: $a = \alpha\sigma$; $b = (\alpha\theta + 2\beta\sigma)$; $c = 2\beta\theta$; we can re-write (8) as:

$$P(t) = at^2 + bt + c \quad (9)$$

By plotting the number of co-publications between country i and country j, against time, and fitting the data with a quadratic equation, we are able to empirically obtain the values of the constants, a, b and c.

In order to determine the time at which the self-organizing network starts working, we re-write (9) in a more convenient way, by introducing some algebraic transformations to the quadratic equation:

$$P(t) = a\left[t + \frac{b}{2a}\right]^2 + \frac{4ac - bc^2}{4a} \quad (10)$$

For simplicity, we introduce a new change of variables $t_0 = -b/2a$ and $\gamma = 4ac - b^2/4a$, and we obtain the following relation:

$$P(t) = a[t - t_0]^2 + \gamma \quad (11)$$

In this way, the minimum of the function (11) will determine the value t_0 at which the self-organizing network dynamics is triggered. To find the value of t_0 we apply the following boundary conditions:

$$\frac{dP(t)}{dt} = 0 \rightarrow t = t_0 \quad (12)$$

and

$$\frac{d^2P(t)}{dt^2} = 2a \rightarrow \begin{cases} a > 0 \rightarrow \text{Min} \\ a < 0 \rightarrow \text{Max} \end{cases} \quad (13)$$

Consequently, the self-organizing co-publication network dynamics will start its process at $t_0 = -b/2a$ with $a > 0$. As it is shown in Table 4 and in Supplementary Tables, all the coupling constants empirically obtained for the co-authorship networks between countries k and i, are such that $a_k^i > 0$, which implies that for all our 352 different cases, t_0 is a minimum of the self-organizing social network.

5. The long-term empirical behaviour of 352 bilateral co-authorship networks

In order to corroborate or falsify the model developed in Section 4, here we analyse the behaviour of 552 different co-authorship networks, that result from studying the cooperation patterns among the 12 Iberoamerican countries of our sample and each of the 46 other nations listed in Table 2.

Assuming that each network will have at least two countries as nodes and several scientific publications as links which will increase quadraticly against time, we analyse the number of publications that results from the cooperation of country k with country i, as a function of time $P_k^i(t)$. From the analysis described in Section 3 we already have the quantity of articles that were co-published for 552 bilateral different networks between 1973 and 2006. Due to the fact that the quantity of mainstream scientific publications in diverse nations is very small, the co-publications among several pairs of countries practically do not exist, consequently, no network can be considered. From the original 552 bilateral co-publications study, in only 352 cases, it is possible to perform a network data analysis.

By fitting the data for each $P_k^i(t)$ distribution with quadratic equations, we can empirically determine the numerical values of the corresponding coefficients a_k^i, b_k^i, and c_k^i. From Eqs. (10)–(12) we calculate the value of t_0 at which the self-organizing network starts (see for example Table 4). Within the Supplementary Tables we present the list of co-authorship networks among the 12 Iberoamerican countries of our sample with all those nations with enough data to perform a quadratic fitting (1973–2006).

These tables include information about the co-authorship country; the number of accumulated co-publications (1973–2006); the percentage $\left[\left(\sum_{j=1973}^{j=2006} P_k^i(t_j) / \sum_{j=1973}^{j=2006} P_k(t_j)\right) * 100\right]$ or the fraction of the total number publications between 1973 and 2006 of country k that was co-published with country i; the coefficients a_k^i, b_k^i, and c_k^i; the time t_0 at which the self-organizing network is triggered; and the correlation coefficient (Weisberg, 1980) $R = cov(P(t_j), t_j)/\sqrt{var(P(t_j))var(t_j)}$, here j indicates years between 1973 and 2006.

Figs. 6–10 show the co-authorship network behaviour of Spain, Brazil, Mexico, Argentina and Portugal (Iberoamerican countries which account for 87.6% of the total mainstream scientific publications of the region). In these figures we represent the total number of co-publications (links) with their main cooperative nations (nodes) against time (1973–2010). The curve fitting was computed using data between 1973 and 2006 (see Table 4 and the complete set at Supplementary Tables). The data between 2007 and 2010 was not included in the curve fitting and added here to

Table 4
Main co-authorship networks of Brazil.

No.	Country	Co-publications (1973–2006)	%	*a*	*b*	*c*	T_o	*R*
1	USA	26662	11.60	0.9775	−3866.117	3822666.5106	1978	0.997
2	France	8511	3.70	0.9897	−3915.519	3872902.1899	1978	0.992
3	United Kingdom	8031	3.49	1.0436	−4132.414	4091037.4820	1980	0.989
4	Germany	6723	2.93	0.5826	−2305.617	2281066.0570	1979	0.994
5	Italy	4344	1.89	0.6344	−2513.442	2489352.0585	1981	0.987
6	Canada	4155	1.81	0.5618	−2224.166	2201380.1368	1979	0.986
7	Argentina	3338	1.45	0.6522	−2585.684	2562686.0997	1982	0.981
8	Spain	3259	1.42	0.6344	−2513.442	2489352.0585	1981	0.987
9	Japan	2296	1.00	0.3568	−1412.698	1398403.1486	1980	0.994
10	URSS/Russia	1981	0.86	0.2985	−1181.060	1168400.3928	1978	0.954
11	Netherlands	1858	0.81	0.3600	−1426.427	1412946.5958	1981	0.983
12	Portugal	1839	0.80	0.4384	−1737.931	1722424.4280	1982	0.974
13	Mexico	1659	0.72	0.2899	−148.607	1137624.2447	1981	0.977
14	Belgium	1635	0.71	0.2056	−813.263	804179.9963	1978	0.988
15	Switzerland	1626	0.71	0.1913	−756.489	747989.4049	1977	0.970
16	Sweden	1452	0.63	0.1914	−757.503	749305.2241	1979	0.985
17	Chile	1440	0.63	0.2031	−804.069	795742.3052	1979	0.970
18	Australia	1373	0.60	0.3314	−1313.979	1302358.6141	1982	0.972
19	India	1086	0.47	0.2249	−891.485	883404.2768	1982	0.963
20	China	1081	0.47	0.2749	−1089.808	1080158.0707	1982	0.984
21	Poland	1057	0.46	0.1192	−471.291	465724.4286	1977	0.967
22	Israel	998	0.43	0.1645	−651.561	645318.5184	1980	0.947
23	Denmark	831	0.36	0.0859	−339.389	335407.5107	1975	0.950
24	Colombia	810	0.35	0.1571	−622.370	616581.0912	1981	0.969
25	Austria	716	0.31	0.0908	−358.089	355063.2028	1972	0.952
26	Finland	614	0.27	0.0538	−212.335	209498.3882	1973	0.948
27	Norway	609	0.26	0.0559	−220.605	217699.6396	1973	0.928
28	Venezuela	604	0.26	0.0888	−351.569	348100.5231	1980	0.954
29	Uruguay	492	0.21	0.1201	−476.384	472294.7166	1983	0.969
30	South Korea	472	0.21	0.1351	−535.928	531337.9024	1983	0.954
31	Jamaica	470	0.20	0.1145	−453.912	448842.3347	1982	0.964
32	Cuba	469	0.20	0.1132	−448.832	444774.5477	1982	0.967
33	Peru	341	0.15	0.0716	−283.969	281449.0659	1983	0.897
34	Ireland	301	0.13	0.0806	−319.726	316993.6786	1983	0.871
35	Costa Rica	205	0.09	0.0471	−186.964	185375.6686	1985	0.895
36	Ecuador	197	0.09	0.0650	−257.949	255854.6161	1984	0.891
37	Panamá	120	0.05	0.0396	−157.214	155950.6608	1985	0.896
38	Bolivia	106	0.05	0.0171	−67.717	67036.2021	1980	0.866
39	Paraguay	35	0.02	0.0185	−73.406	72747.7876	1984	0.815
40	Guatemala	32	0.01	0.0070	−27.744	27510.9331	1982	0.758

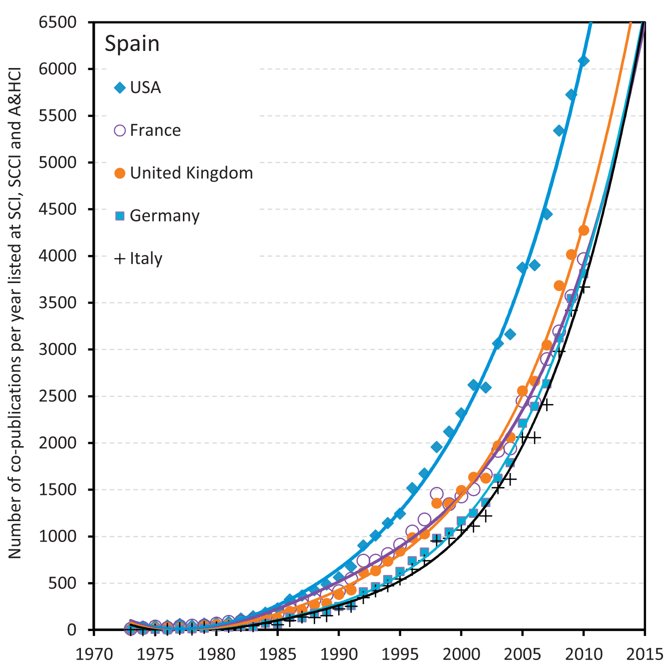

Fig. 6. Temporal evolution (1973–2010) of the co-authorship social network of Spain. Here we represent the number of co-publications against time for the 5 most important cooperative nodes (countries). The model developed predicts a parabolic growth in the number of links (publications) against time. Here the solid lines represent the quadratic fitting (1973–2006) according to our model.

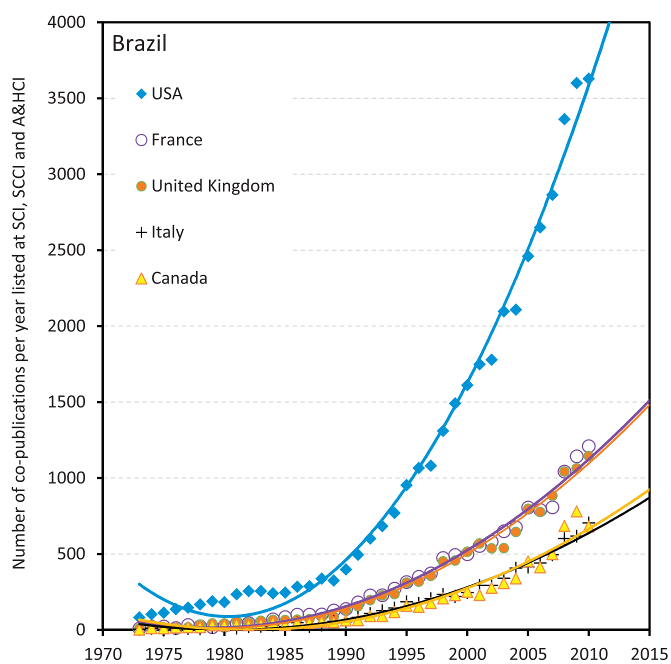

Fig. 7. Temporal evolution (1973–2010) of the co-authorship social network of Brazil. Here we represent the number of co-publications against time for the 5 most important cooperative nodes (countries). The model developed predicts a parabolic growth in the number of links (publications) against time. Here the solid lines represent the quadratic fitting (1973–2006) according to our model.

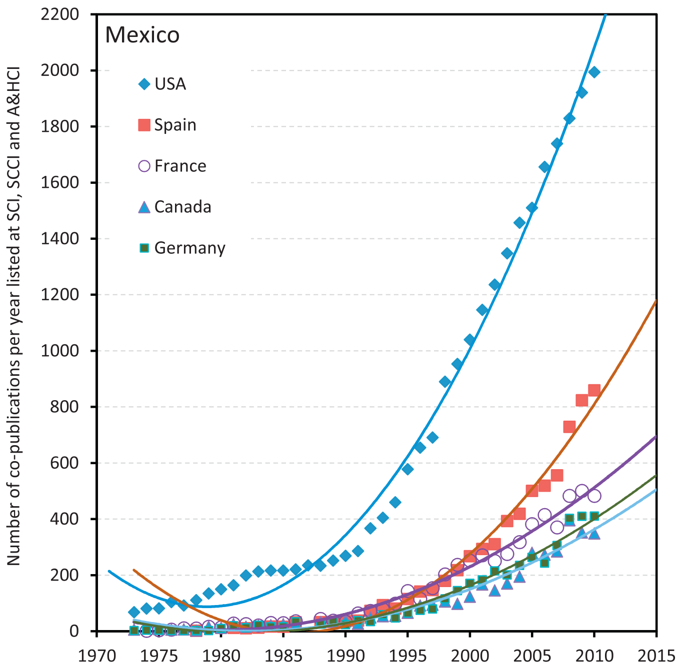

Fig. 8. Temporal evolution (1973–2010) of the co-authorship social network of Mexico. Here we represent the number of co-publications against time for the 5 most important cooperative nodes (countries). The model developed predicts a parabolic growth in the number of links (publications) against time. Here the solid lines represent the quadratic fitting (1973–2006) according to our model.

test the theoretical prediction of our model with four years of data. Figs. 6–10 show the great adjustment that the data between 2007 and 2010 have with each continuous line (model projections).

It is self-evident how well the scale-free self-organizing network model fits the empirical data over 38 years. The minimum of these curves shows the value of t_0 at which the network

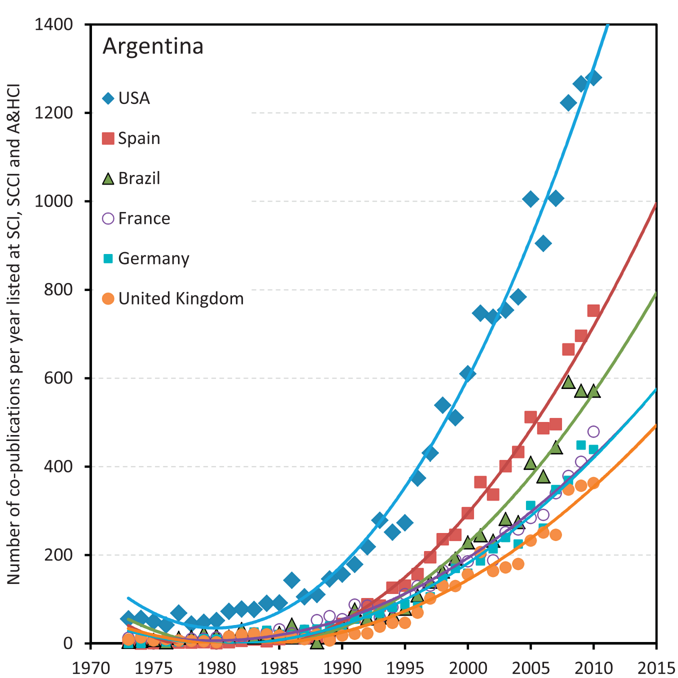

Fig. 9. Temporal evolution (1973–2010) of the co-authorship social network of Argentina. Here we represent the number of co-publications against time for the 6 most important cooperative nodes (countries). The model developed predicts a parabolic growth in the number of links (publications) against time. Here the solid lines represent the quadratic fitting (1973–2006) according to our model.

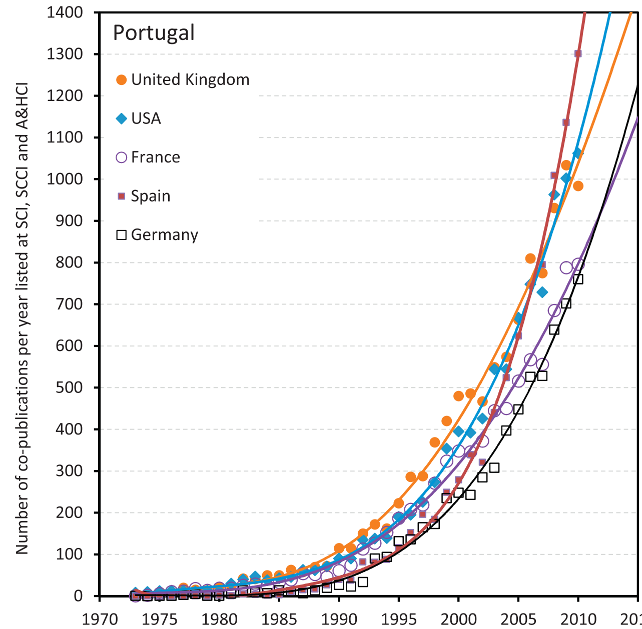

Fig. 10. Temporal evolution (1973–2010) of the co-authorship social network of Portugal. Here we represent the number of co-publications against time for the 5 most important cooperative nodes (countries). The model developed predicts a parabolic growth in the number of links (publications) against time. Here the solid lines represent the quadratic fitting (1973–2006) according to our model.

dynamics is triggered behaving as a self-organizing process. According to this interpretation, the scientific collaborations for $t < t_0$ is below the threshold of connectivities needed to start the self-organizing process. For this reason, we also observe some sort of random behaviour in the $P_k^i(t < t_0)$ values.

From the values of the growth coupling constants a_k^i (see Table 4 and Supplementary Tables)); we can also verify the existence of the preferential attachment effect, where the connectivity of Iberoamerican countries with "hubs" or larger scientific networks (i.e. USA, UK, France, Germany, Spain, etc.) is growing faster than with other less connected countries (smaller scientific networks). The last is another prediction of the model that is corroborated by our empirical study.

Using the data from the 352 networks (see Supplementary Tables) we also empirically find that the total number of co-publications between countries k and i, scales with a power-law with the coupling growth constant a_k^i as $P = 5134.2a^{0.9655}$ (see Fig. 11). The last relation implies that the co-publications with "hubs" (i.e. USA, UK, France, Germany, etc.) growth hyperbolically much faster than with the rest of minor co-authorship networks. This fact is coherent with a preferential attachment strategy as it is predicted by our model.

When we analyse the distribution of the dates, t_0 at which the self-organizing network dynamics is triggered, among the 352 different networks, we find a normal distribution (see Fig. 12) with the most probable value at $t_0 = 1981.4 \pm 2.2$. The first obvious conclusion indicates that the appearance of Internet was not a key issue for the emergence of co-authorship scientific networks dynamics. According to Laudel (2001), most of the scientific collaborations begin face-to-face. Historically relationships, former colonial ties and geographic proximity can only account for the internal Iberoamerican collaboration links (i.e. most of the cooperation with smaller co-authorship networks), but not for the co-authorship dynamics with "hubs." For the latter, a preferential attachment generated by a brain-drain process is still the best explanation. As it was shown previously, there is an increasing set of new evidence showing that migration and mobility of researchers

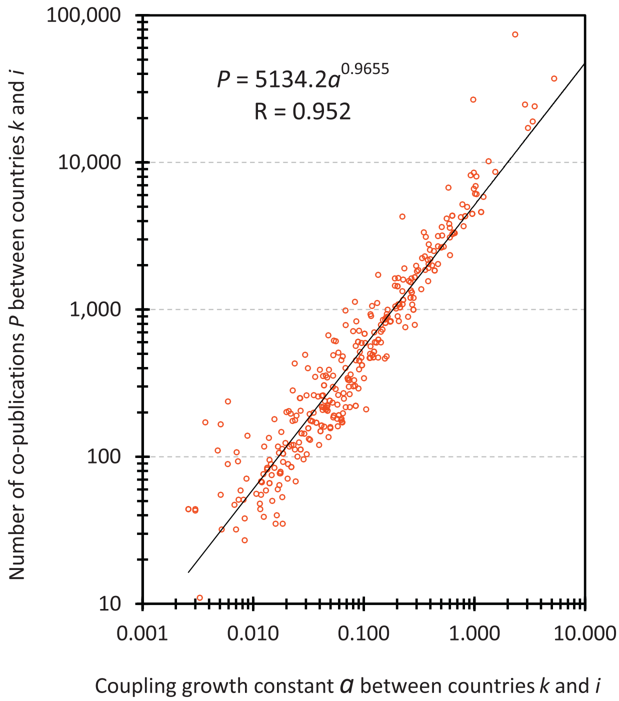

Fig. 11. Power-law (scale-free) distribution total number of co-publications P_k^i, for each of the 352 co-authorship social networks, against the coupling constants a_k^i, according to the data taken from the Supplementary Tables.

and scientists towards the mainstream scientific countries (hubs), expands the connectivities between the original country and a most visible and larger scientific network. This is probably the mechanism that triggers this scientific network dynamics.

Based on relations (10), (11) and (12), we know that there is a lower threshold of connectivities needed to trigger the self-organizing co-authorship network between two countries. According to the normal distribution shown in Fig. 12, most of the co-authorship networks in Iberoamerican countries begun within a short period of time (1981.4 ± 2.2). This effect might be explained by the massive brain-drain movement towards highly developed countries (Oteiza, 1971). In many cases, this emigration was

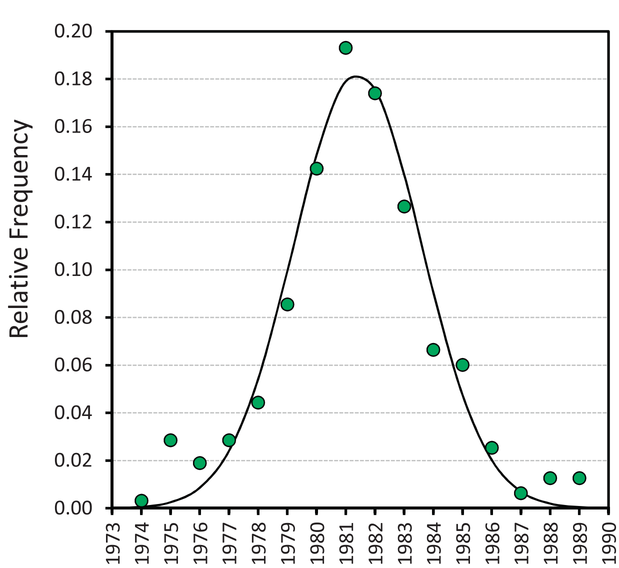

Fig. 12. The dates (t_0) at which the co-authorships social networks start working as a self-organizing process, for the 352 scientific networks (see Supplementary Tables) follows a normal distribution around year 1981.4 ± 2.2.

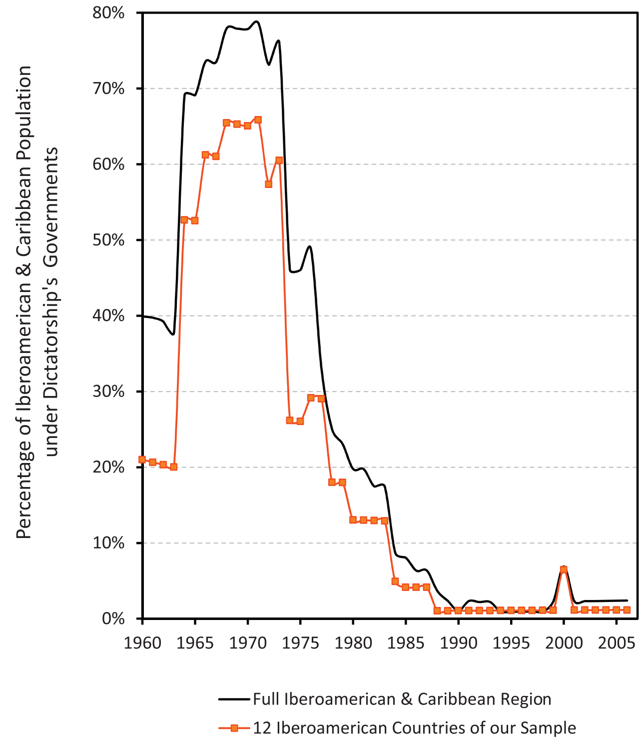

Fig. 13. Percentage of the whole Iberoamerican and Caribbean countries population, living with Dictatorship's Governments, against time. We also represent the evolution of the Dictatorship's Governments among the 12 Iberoamerican countries of our sample expressed as a percentage of their whole population.

generated by the adverse political situation in most Iberoamerican nations, between the late sixties and mid-eighties.

To show the severity of the last situation, in Fig. 13 we estimate the percentage of the whole Iberoamerican and Caribbean population that was living under dictatorships (1960–2006). The continuous line represents $\left(\sum_j I_j^D(t)/\sum_j I_j(t)\cdot 100\right)$, where $I_j^D(t)$ indicates the population as a function of time (1960–2006) of countries j that had a dictatorship government D at time t, and $\sum_j I_j(t)$ the temporal evolution of the population of all the countries j, that in this case are all those listed in the Footnote 1 (whole Iberoamerican and Caribbean population). The continuous line with squares, represents $\left(\sum_k I_k^D(t)/\sum_k I_k(t)\cdot 100\right)$, where $I_k^D(t)$ indicates the population as a function of time (1960–2006) of country k from our sample of 12 Iberoamerican nations, that had a dictatorship government D at time t, and $\sum_k I_k(t)$ the temporal evolution of the populations of all the countries from our sample.

Economic factors and individual mobility, intra-scientific factors and changing communication among scientists also have strong effect on co-operation (Beaver and Rosen, 1978; Beaver, 2001, 2004). Between the mid-sixties and mid-eighties, the Iberoamerican Region was dominated by a very difficult and delicate political and economic situation, which expelled most of their highly qualify talents (in science, technology, medicine, arts, literature and culture in general). The absence of academic freedom, the persistence of ideological harassment, an unstable macro-economic performance, low research budgets and wages, and erratic S&T policies, constituted an extremely powerful driving-force for emigration (push-factors). These effects were also amplified by those pull-factors described in Section 3. To corroborate these effects, Lemarchand (2010) presented a complete analysis of the evolution of STI policies and S&T institutions in Latin America and the Caribbean over the last sixty years. The study was based on a cross correlation analyses using a complete set of different long-term temporal series of economic, social, political and STI indicators for the LAC region which is in a complete agreement with the results presented here.

After living for some time in developed nations, and participating in larger R&D networks, those expatriate scientists, engineers and technicians generated a critical mass of connectivities that trigged the co-authorship network dynamics, linking Diaspora members with scientists in their original countries.

6. Forecasting methods to study the scientific co-publication patterns among countries

If the co-publication at time t of country k with two countries i and j, have coupling coefficients $a_k^i > a_k^j$, we will obtain $P_k^i(t) > P_k^j(t)$ for every $t > t_0$. But if the coupling coefficients have the following property $a_k^i < a_k^j$, we can estimate the time t_{int} at which both countries i and j have the same number of co-publications with country k or $P_k^i(t_{\text{int}}) = P_k^j(t_{\text{int}})$. After this time ($t_f > t_{\text{int}}$) the number of co-publications of country k with countries i and j will have the following opposite relation: $P_k^i(t_f) < P_k^j(t_f)$.

Here-on we estimate the value of t_{int} as a function of the values $a_k^i, a_k^j, b_0^i, b_0^j, c_k^i, c_k^j$ that are empirically determined and listed in Table 4 (to have access to the whole set at Supplementary Tables).

If

$$P_k^i(t_{\text{int}}) = P_k^j(t_{\text{int}}) \tag{14}$$

From (9) and (14) we have

$$a_k^i t_{\text{int}}^2 + b_k^i t_{\text{int}} + c_k^i = a_k^j t_{\text{int}}^2 + b_k^j t_{\text{int}} + c_k^j \tag{15}$$

and

$$0 = \left(a_k^j - a_k^i\right) t_{\text{int}}^2 + \left(b_k^j - b_k^i\right) t_{\text{int}} + \left(c_k^j - c_k^i\right) \tag{16}$$

Introducing the following changes of variables:

$$\begin{cases} \mu = \left(a_k^j - a_k^i\right); \\ \rho = \left(b_k^j - b_k^i\right); \\ \omega = \left(c_k^j - c_k^i\right); \end{cases} \tag{17}$$

We finally can determine the value of t_{int} as:

$$t_{\text{int}} = \frac{-\rho + \sqrt{\rho^2 - 4\mu\omega}}{2\mu} \tag{18}$$

Here we need to consider only the major real root of Eq. (18) that corresponds to the moment at which a smaller co-authorship network ($P_k^i(t) > P_k^j(t)$) but with a higher growth coupling coefficient, $a_k^i < a_k^j$, reaches the same annual co-publications rate than the biggest one ($P_k^i(t) = P_k^j(t)$).

We apply this methodology to a particular substitution case to show how it works. For many years, the second main co-authorship country of Spain was France, but recently the last was replaced by the United Kingdom (see Fig. 6). Here we apply our formalism to estimate t_{int} by using the coefficients taken from Table 4: $a_{\text{Spain}}^{\text{France}} = 2.8737$, $b_{\text{Spain}}^{\text{France}} = -11364.005$, $c_{\text{Spain}}^{\text{France}} = 11234641.97$, $a_{\text{Spain}}^{\text{UK}} = 3.5101$, $b_{\text{Spain}}^{\text{UK}} = -13893.87$, $c_{\text{Spain}}^{\text{UK}} = 13748708.15$, and replacing them into Eqs. (17) and (18). In this way, we can theoretically estimate when Spain reached a higher number of co-publications with the UK rather than with France as $t_{\text{int}} = 1998.9$. This methodology can be used with any set of a_k^i, b_k^i, c_k^i coefficients, that represent the growth constants of the co-publications of country k with a group of countries i.

The last can be a very useful tool for S&T planners and for any other decision-makers.

7. Summary and discussion

We have studied the long-term behaviour of mainstream knowledge production for all Iberoamerican and Caribbean countries between 1973 and 2010. During the last decade, only two nations of the Iberoamerican region (Spain and Brazil) were included in the top-twenty most productive countries of the world. We showed that the production of scientific articles in mainstream journals against time follows exponential growth behaviour, where Portugal, Colombia, Spain and Brazil, got the highest growth rates. The rest of the Iberoamerican nations presented a more irregular behaviour that was directly correlated with their national macroeconomic and political performances across the examined years.

We also analysed the evolution of the national productivity, in terms of the number of articles per million-inhabitants. Again, we found the excellent performance of the two European nations of our sample. Portugal increased its productivity 64 times during a 38-year period and was seconded by Spain with 47 times. Both countries received the benefits of participating in the European Community Scientific Programs, which favoured their continuous growth. Table 3 showed a very interesting difference between Spain and Portugal that may explain one of the causes of the higher growth slope of the last one. When we compare the traffic coefficient numbers (the ratio between the percentages of co-publications with larger scientific networks over the percentages of co-publications with smaller ones) Spain showed a 2.1 value, while Portugal the amazing 90.2 one. The strategy followed by Portugal to associate only with hubs or other larger networks only (preferential attachment) got the prize of a higher visibility, more opportunities to work in hot topics, great expansion of their connectivities and the possibility to share with Mexico (ten times Portugal's population) the third rank of the region, in the number of mainstream publications per year.

Within Latin America, Chile, Argentina and Uruguay have the highest productivity, but their behaviour presented some irregular shapes, that were in agreement with their internal economic and political performances during the same period. The productivity of the two most populated countries of the region, Brazil (203-million) and Mexico (113-million), are below the previously mentioned ones. However, they are also experiencing a continuous exponential growth-rate that will allow them to reach the highest Latin American productivities in just a few years. Between 2008 and 2010, Brazil almost reached the same productivity of Uruguay. Another interesting case was Colombia, which after introducing some structural reforms to the national science and technology system, got the second nominal highest growth-rate, after Portugal. Nevertheless, in the last case, the productivity still remains very low. We should mention here that two small Caribbean islands, Grenada and Barbados, with a modest scientific production and a very small population, have a higher productivity that is comparable with Chile's.

On the other hand, we have Jamaica and Venezuela, whose productivities remained practically constant during the whole 38-year period. We think that this is a good indicator of the absence of S&T policies or just their failure.

We also studied, with great detail, the co-publication profiles of 12 Iberoamerican countries that account for the 98% of the whole regional mainstream knowledge production (1973–2010). Within the last sample we considered all the Iberoamerican countries in which their individual total production for the period was over 0.5% of the total aggregated number of publications for all Iberoamerican and Caribbean countries between 1973 and 2010 (see Fig. 1). We analysed the cooperation patterns of each country of the sample with other 46 different countries. We showed that the USA, the UK, France, Germany, Spain and Brazil, work like real hubs for all the Iberoamerican and Caribbean countries, concentrating the great majority of co-authorship activities.

We also found that most of the co-publications were performed with extra-regional countries and we detected a shift, in the last decade, that favoured the increase of intra-regional cooperation, as well as the emergence of new co-authorship networks with countries such as South Korea, Russia, China, Czech Republic, India, etc. The first may be explained by the existence of new regional cooperation agreements and programs, while the second by the globalization of knowledge production processes.

We showed that the scientific co-authorship among countries follows a power-law and behaves as a self-organizing scale-free network, where each country appears as a node and each co-publication as a link. We developed a mathematical model to study the temporal evolution of co-authorship networks, and we showed that the number of co-publications among countries growths quadraticly against time. We determined the boundary conditions at which the self-organizing network process is triggered.

We empirically corroborated the quadratic growth prediction of our model by analysing a 38-year temporal evolution of 352 different co-authorship networks. We showed how the number of co-publications $P_k^i(t)$ between country k and country i, are related with a power-law against the coupling growth coefficients a_k^i (scale-free). We calculated the quadratic growth coefficients a_k^i, b_k^i, c_k^i, for 352 different pairs of co-authorship countries across 34 years (1973–2006).

The last original results may be employed to estimate the future co-authorship behaviour of mainstream scientific articles for the Iberoamerican countries. We have also presented a mathematical methodology to use the empirically determined growth constants of each co-authorship network (see Table 4 and the complete set at Supplementary Tables), to predict changes in the relative intensity of cooperation among different countries. All of the above constitutes a very useful set of tools that can be used by S&T planners and decision-makers worldwide.

We calculated that the 47% of the networks have correlation coefficients with $R > 0.94$; 27% with $0.94 > R > 0.90$; 18% with $0.90 > R > 0.84$ and 8% with $R < 0.84$. These results show a very good agreement between our mathematical model and all the fitted data over a 34-year period.

We also corroborated the prediction that the connectivity of regional countries with larger scientific networks grows faster than with other less connected countries. We determined that 70.4% of the 352 analysed cases linked their cooperation with hubs or larger co-authorship networks. These social webs were responsible for 39.6% of the total number of articles that were published, between 1973 and 2006, by the 12 countries of our sample. The rest of the co-authorship networks (smaller ones) accounted for only 8.8% of the total regional production. Spain, alone, concentrated 6.1% of the last 8.8%.

These smaller scientific co-authorship networks are composed by Latin American countries, where historical relationships, former colonial ties, same language and geographic proximity, can justify their existence. All these results are, again, consistent with the preferential attachment dynamics proposed as the bases of our mathematical model.

We think that the type of internal dynamics described by our mathematical model explains by itself the self-organizing property of the co-authorship scientific networks. Similar conclusions were obtained independently by Katz (1999) and Wagner and Leydesdorff (2005a). In order to estimate how the explicit S&T policy regional cooperation instruments work, or not, Lemarchand (2005) proposed to correlate output S&T indicators (i.e. bibliometric co-authorship) with the application of international cooperation agreements and programs. Unfortunately, the lack of regional databases with complete lists of all international scientific cooperation agreements among institutions and countries, did not allow us to test them in a systematic way.

In spite of the fact that we lacked complete regional databases, we used information provided by Lemarchand (2005, pp. 125–127) to analyse if there was any influence on intra-regional cooperation performance from those agreements between Argentina and the rest of Latin American & Caribbean countries (1965–2004). We found that the temporal evolution of formal S&T regional cooperative agreements (RCA) increases its size in a linear way, such as: $RCA = 3.5037t - 6.7079$ ($R = 0.997$), where t is time in years. The fact that RCA follows a linear growth like equation (1), and that the first might be embedded in the last, inhibit us to evaluate if the quadratic growth detected for the cooperation between Argentina and the rest of Iberoamerican countries (Lemarchand, 2010: p. 75) was influenced by the RCA or not. In order to formally reject its influence, we need to count each single mainstream scientific article that resulted from all these formal RCA. The last information was not available.

At this point we agree with Wagner and Leydesdorff (2005a) that the explicit S&T policies and other classical models cannot account for the scientific co-authorship network dynamics. The analysis over 38-year period that is provided in this article, of 352 different scientific co-authorship networks, presents enough evidence for the argument that the dynamics of regional co-publication are a self-organizing process that is governed by a preferential attachment.

We also applied our mathematical model to estimate the dates, t_0, at which the co-authorship connectivities trigger the self-organizing scale-free network for each of the 352 cases (Supplementary Tables). We found that the last follows a normal distribution around year 1981.4 ± 2.2. We associated this particular concentration of dates which trigger the self-organizing co-authorship networks, with a massive brain-drain caused by the adverse regional political situation, between the mid-sixties and mid-eighties, where more than 70% of the Iberoamerican and Caribbean population were living under Dictatorship's Governments (see Fig. 13). We have examined, both, the pull and push factors for the international mobility and migration of talents, during those days.

The examined data showed a time-lag of $\approx$15 years, between the peak when most of the Iberoamerican population was living under dictatorships (massive brain-drain) and the peak when most of the co-authorship networks were triggered. We believe that emigrant scientists living abroad need a period of time in order to develop a wide range of S&T human capital assets, to enhanced S&T knowledge, craft skills and know-how, to publish mainstream articles, to develop their ability to structure and plan research and of course, to increase contacts with other scientists, the industry, and funding agents. After expanding these potentialities, the emigrant scientists become "visible" to the scientific networks of their home-country. After this time-lag, they may be in a position to begin transferring part of their accumulated knowledge and experience to their home-country, through periodic visits and by participating in knowledge and co-authorship networks. The latter "working hypothesis" can be tested or rejected by future empirical work.

In recent years, several Latin American countries established a wide range of national programs (such as CALDAS in Colombia; RAICES in Argentina; Red de Talentos para la Innovación in Mexico, Chile Global; Science without Borders: The Brazilian Scientific Mobility Program at CNPq and MCT; etc.) with the strategic objective of coordinating and stimulating the scientific Diasporas in order to strengthen knowledge networks with their home countries. These S&T policies have also the possibility to enhance the self-organizing mechanisms of co-authorship networks and transform brain-drain into brain-gain. This knowledge may have useful applications for designing new STI policy instruments in the future.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.respol.2011.10.009.

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