Chapter 2
The Scientific Productivity and the Dynamics of Self-organizing Networks: Ibero-American and Caribbean Countries (1966–2013)

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2.1 Production Knowledge in Mainstream Journals (1966–2013)

To understand the behavior of scientific productivity among various Ibero-American and Caribbean countries, this study analyzes the evolution of the production of scientific articles published in mainstream journals in all fields of knowledge. The analysis covers the period from 1966 to 2013.

Within the study period, more than 99 % of the publications listed in mainstream journals were produced by just 15 countries. Taking into account the historical, economical, and cultural links of the diverse countries within this sample, at least three groups can be distinguished: (a) European countries (Spain and Portugal); (b) Latin American countries; and (c) developing small-island states in the Caribbean. The scientific productivity of the different states in this sample relates to the national levels of industrialization, higher education, and research policies developed over the last five decades.

In this article, the focus of the study is on the production of citable scientific articles in all fields of knowledge. To study the distribution of publications in each

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Table 2.1 World publication rankings using WoS data for a selected group of Ibero-American countries (1970–2012)

Country	1970[a]	1975	1980	1985	1990	1995	2000	2005	2010	2011	2012
Spain	29	26	19	15	13	10	10	9	10	10	10
Brazil	30	27	27	27	24	21	17	17	13	13	13
Portugal	46	46	47	45	42	39	37	34	32	27	26
Mexico	35	35	34	35	35	31	29	28	29	30	31
Argentina	27	28	29	29	32	35	33	39	39	39	40
Chile	33	36	36	36	40	44	42	43	45	46	46
Colombia	51	89	55	52	56	59	56	56	51	50	49
Venezuela BR	32	41	41	43	45	50	51	53	62	65	65
Cuba	84	68	62	59	57	55	52	58	65	63	64
Peru	53	59	63	68	59	88	81	78	72	73	75

Source: Estimations by the author based on raw data provided by WoS

[a]Based on information provided by De Solla Price (1986)

Ibero-American and Caribbean country,[1] Thomson-Reuters' Web of Science[2] (WoS) is used as the information source. Particularly, articles listed in the Science Citation Index Extended (SCI), Social Science Citation Index (SSCI), and the Arts and Humanities Citation Index (A&HCI) were examined. These databases constitute an appropriate and qualified indicator to investigate knowledge–production patterns within the region.

Table 2.1 shows the evolution of the world rankings in terms of number of publications listed in the WoS for the ten most prolific countries in the sample.

Within the analyzed period (42 years) shown in Table 2.1, Colombia moved up 40 places in the world ranking for number of publications, with Portugal moving up 20, Spain 19, Brazil 17, and Mexico and Cuba 4. In contrast, Venezuela fell 33 places, Peru 25, Argentina 17, and Chile 13. The relative position within the world ranking depends on the endogenous behavior of each individual country and the growth dynamics of other countries worldwide. For this global ranking, the same measurement method was used for countries with very different population,

[1]The countries included here for analysis within the Ibero-American 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, 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 the Bolivarian Republic of Venezuela. These countries were studied to estimate the total number of regional publications per year (1966–2013). A number of nations were excluded from the study: Puerto Rico (with 18,442 publications over the period) because it is a territory of the United States, French Guiana (with a total number of 1,179 publications over the period), and the Caribbean colonial states (Anguilla, Aruba, British Virgin Islands, Cayman Islands, Curaçao, Guadeloupe, Martinique, Montserrat, Saint Martin, and Turks and Caicos). Most of the smaller Caribbean islands had no mainstream scientific publications during this period.

[2]http://thomsonreuters.com/thomson-reuters-web-of-science/

economic, and development levels. This is the main limitation of such scoreboards. The results can be misleading if this restriction is not taken into account; most scoreboards and world rankings do allude to this issue.

In the present chapter, it is made clear that each individual country has its own dynamics. To test this hypothesis, the different growth rates of the scientific articles published in mainstream journals will be analyzed.

Figure 2.1 shows the distribution of published articles between 1966 and 2013 with a log-linear scale for the 18 Ibero-American nations with the highest number of mainstream scientific publications. This sample includes more than 99 % of the total number of publications published within the same period. The distribution

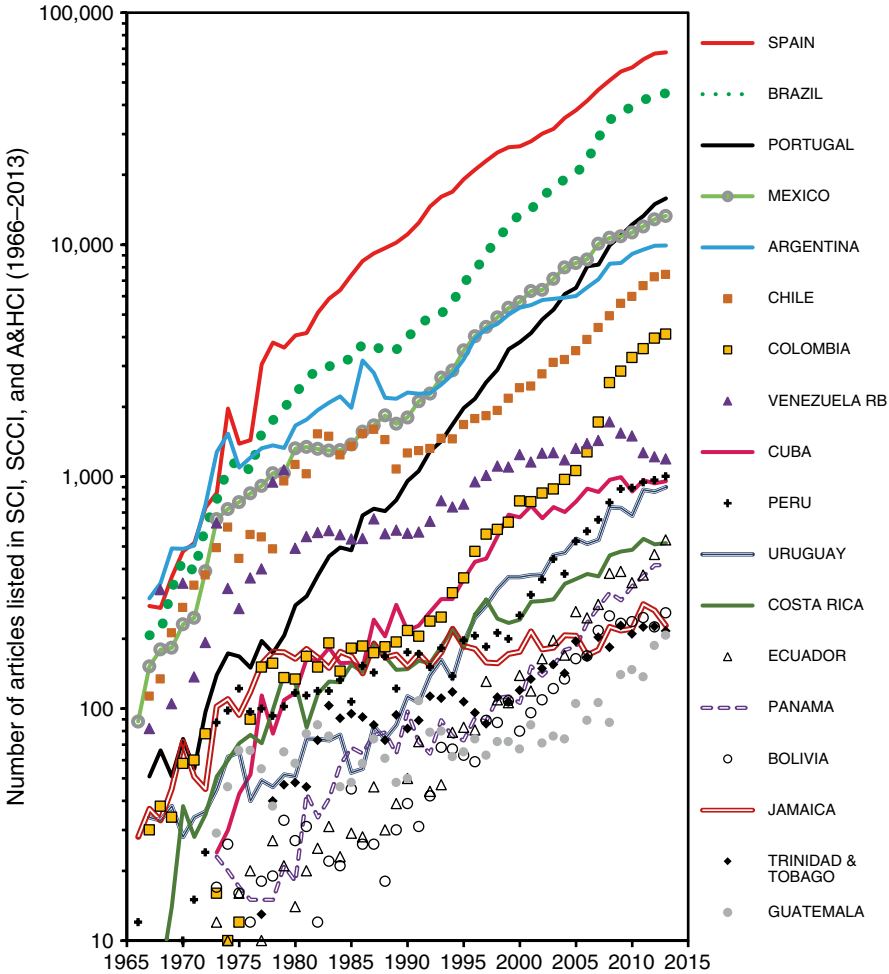

Fig. 2.1 Publication of peer-reviewed articles listed in SCI, SSCI, and A&HCI for the 18 most productive Ibero-American and Caribbean countries (1966–2013) (exponential growth); Portugal shows the highest growth rate

follows an exponential growth behavior, 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, and φ and γ are empirically determined constants.

Table 2.2 shows the 30 most productive Ibero-American and Caribbean countries in terms of scientific publications listed in SCI, SSCI, and A&HCI between 1966 and 2013. The first column indicates the country ranking according to the total number of articles published (1966–2013). The third column shows the total number of articles published (Δ_1: 1966–2013) while the fourth shows the shares of each country in the same period. The fifth column shows the total number of articles published in the last decade (Δ_2: 2004–2013) and the sixth column the corresponding shares. The seventh column represents the size of publications over the last decade as a percentage of the total number of publications over the whole period (Δ_2/Δ_1). The eighth column covers the number of publications during 2013 and the ninth the corresponding shares. The following six columns present the exponential growth rates (ρ, σ, λ) and their corresponding determination coefficients ($R^2_{\rho,\sigma,\lambda}$) to measure: (1) the growth in the number of citable publications over time (ρ and R_ρ^2); (2) the growth in the number of citable publications per million inhabitants over time (σ and R_σ^2); and (3) the growth in the ratio between the number of citable publications and GDP per capita in 2005 constant US dollars (λ and R_λ^2) over time. The population and GDP data used for these computations for each country and each year between 1966 and 2013 were sourced from the UN Statistics Division.

Interestingly in this calculation, the data analyzed cover a period close to five decades (48 years). For the most productive countries in the sample, the critical mass of researchers—according to their population size—was reached in the early 1980s (Lemarchand 2007, 2012). By including data between 1966 and 1980, the fitting coefficients are diminished because the system was not operating in the self-organizing regime owing to the lack of critical mass of researchers. However, by extending the analyzed period, other features can be detected. Changes in the slope of the different growth curves are usually associated with changes in economic, social, and political conditions within the different countries. Some of these changes are also associated with the application of specific policies for the promotion of scientific research and technological development (Lemarchand 2010).

Portugal has the highest ρ, σ, and λ growth constants of the sample. This is consistent with previous results (Lemarchand 2012). In these three cases, they show exponential growth with fitting determination constants $R^2_{\rho,\sigma,\lambda} > 0.99$. Within a period of 48 years, Portugal increased its publications by a factor of 311, its publications per million inhabitants by a factor of 247, and the ratio between the publications and GDP per capita in constant 2005 USD by a factor of 92. In 1966, Portugal ranked seventh for publications in the region; by 2013 it had moved to third place, overtaking Mexico, with a population 10 times the size of Portugal.

Spain has the second-highest growth rate for the number of publications and publications per capita, and the fourth-highest growth rate in terms of the ratio between publications and GDP per capita. Brazil has the third-highest growth rate in publications, the fourth for publications per capita, and the fifth for the ratio of publications/GDP per capita.

Table 2.2 Scientific productivity expressed by a set of selected indicators for three periods: 1966–2013, 2004–2013, and 2013

		Δ_1 : 1966–2013		Δ_2 : 2004–2013		Δ_2/Δ_1	2013		1966–2013		1966–2013		1966-2013	
Rank	Country	No. of articles	% Regional	No. of articles	% Regional	[%]	No. of articles	% Regional	ρ	R_ρ^2	σ	R_σ^2	λ	R_λ^2
1	Spain	914,613	41.64	523,614	40.58	57.25	67,439	39.58	0.1134	0.94	0.1082	0.93	0.0935	0.92
2	Brazil	508,482	23.15	333,489	25.85	65.59	44,949	26.38	0.1073	0.97	0.0898	0.96	0.0914	0.98
3	Mexico	187,601	8.54	106,052	8.22	56.53	13,299	7.80	0.0925	0.96	0.0730	0.94	0.0799	0.96
4	Argentina	170,252	7.75	80,644	6.25	47.37	9,909	5.82	0.0650	0.93	0.0521	0.90	0.0628	0.90
5	Portugal	150,550	6.85	106,156	8.23	70.51	15,848	9.30	0.1280	0.99	0.1240	0.99	0.1032	0.99
6	Chile	98,679	4.49	52,794	4.09	53.50	7,441	4.37	0.0710	0.91	0.0558	0.86	0.0405	0.66
7	Venezuela	37,829	1.72	13,774	1.07	36.41	1,193	0.70	0.0446	0.74	0.0209	0.40	0.0505	0.78
8	Colombia	35,071	1.60	25,330	1.96	72.22	4,118	2.42	0.1055	0.90	0.0850	0.84	0.0868	0.85
9	Cuba	17,770	0.81	8,915	0.69	50.17	955	0.56	0.0821	0.92	0.0785	0.92	0.0732	0.87
10	Peru	12 865	0.59	7,604	0.59	59.11	1,003	0.59	0.0849	0.85	0.0646	0.76	0.0798	0.83
11	Uruguay	11,756	0.54	6,844	0.53	58.22	900	0.53	0.0791	0.95	0.0738	0.94	0.0623	0.93
12	Costa Rica	9,741	0.44	4,446	0.34	45.64	517	0.30	0.0688	0.85	0.0453	0.71	0.0515	0.75
13	Jamaica	7,598	0.35	2,200	0.17	28.95	228	0.13	0.0312	0.62	0.0224	0.47	0.0885	0.96
14	Ecuador	5,276	0.24	3,454	0.27	65.47	534	0.31	0.0968	0.97	0.0742	0.94	0.0885	0.96
15	Panama	5,120	0.23	3,024	0.23	59.06	416	0.24	0.0800	0.94	0.0587	0.88	0.0630	0.88
16	Trinidad & Tobago	4,482	0.20	1,996	0.15	44.53	216	0.13	0.0664	0.63	0.0611	0.59	0.0506	0.44
17	Bolivia	3,605	0.16	2,136	0.17	59.25	259	0.15	0.0988	0.84	0.0775	0.75	0.0975	0.83
18	Guatemala	3,311	0.15	1,279	0.10	38.63	207	0.12	0.0630	0.51	0.0389	0.28	0.0098	0.57
19	Barbados	1,915	0.09	782	0.06	40.84	94	0.06	0.0681	0.72	0.0652	0.69	0.0006	0.61
20	Nicaragua	1,183	0.05	733	0.06	61.96	79	0.05	0.0898	0.88	0.0691	0.81	0.1028	0.89
21	Paraguay	1,124	0.05	670	0.05	59.61	105	0.06	0.0707	0.84	0.0543	0.67	0.0555	0.72
22	Dominican Republic	1,118	0.05	528	0.04	47.23	88	0.05	0.0665	0.77	0.0465	0.61	n/a	n/a

(continued)

Table 2.2 (continued)

Rank	Country	Δ_1 : 1966–2013		Δ_2 : 2004–2013		Δ_2/Δ_1	2013		1966–2013		1966–2013		1966-2013	
		No. of articles	% Regional	No. of articles	% Regional	[%]	No. of articles	% Regional	ρ	R_ρ^2	σ	R_σ^2	λ	R_λ^2
23	Honduras	1,066	0.05	558	0.04	52.35	82	0.05	0.0515	0.64	0.0244	0.26	0.0411	0.53
24	Bermuda	776	0.04	309	0.02	39.82	41	0.02	0.0455	0.69	0.0396	0.60	0.0281	0.46
25	El Salvador	735	0.03	425	0.03	57.82	54	0.03	0.0406	0.32	0.0268	0.15	0.0290	0.23
26	Haiti	724	0.03	436	0.03	60.22	78	0.05	0.0715	0.76	0.0506	0.60	n/a	n/a
27	Grenada	654	0.03	595	0.05	90.98	115	0.07	0.1058	0.57	0.0956	0.51	n/a	n/a
28	Guyana	611	0.03	226	0.02	36.99	19	0.01	0.0297	0.53	0.0295	0.53	0.0213	0.34
29	Bahamas	353	0.02	191	0.01	54.11	40	0.02	n/a	n/a	0.0312	0.28	n/a	n/a
30	Belize	308	0.01	184	0.01	59.74	25	0.01	0.0819	0.73	n/a	n/a	n/a	n/a

Following this first group (Brazil, Portugal, and Spain), it is interesting to observe that Grenada, Colombia, Bolivia, and Ecuador have the next highest growth rates in terms of publications and publications per capita.

In contrast, Guyana, Jamaica, and the Bolivarian Republic of Venezuela have the lowest ρ, σ, and λ constant rates. In these cases, the number of citable publications per million inhabitants had increased by less than a factor of two over the last 40 years.

In terms of the shares of publications over the whole region, three different periods are studied (1966–2013, 2004–2013, and 2013). Spain remained relatively constant, producing approximately 40 % of the publications, while the shares of Brazil, Portugal, Colombia, Ecuador, and Grenada increased. In contrast, those of Mexico, Argentina, Venezuela, Cuba, Costa Rica, Jamaica, Trinidad and Tobago, Bermuda and Guyana decreased. The shares of the rest of the countries remained constant across the three periods.

A very important feature is the fact that in several countries, the majority of the scientific production occurred in the last decade (see Δ_2/Δ_1). The most extraordinary case was that of Grenada with 91 %, followed by Colombia (72 %), Portugal (71 %), Brazil (66 %), Ecuador (65 %), Nicaragua (62 %), Haiti (60 %), Belize (60 %), and Paraguay (60 %). Bolivia, Peru, Panama, Uruguay, El Salvador, Spain, Mexico, Bahamas, Chile, Honduras, and Cuba present shares between $59\ \% \geq \Delta_2/\Delta_1 \geq 50\ \%$. The remainder of the countries have shares below 50 %.

These bibliometric measurements belong to the science and technology (S&T) output indicators set (Freeman 1969). The study of these measurements represents, in many ways, the performance of the national production of knowledge stemming from research and development (R&D) activities. The absence of growth for more than four decades (i.e., Venezuela and Jamaica) implies the failure of the applied S&T policies. In contrast, the research and innovation policies applied in Spain, Brazil, and Portugal present relative success, as shown by the temporal evolution of most of their main S&T indicators, such as R&D funding, number of full-time equivalent (FTE) researchers, higher education policies, generation of new PhDs, and by the increase in the number of scientific publications (Lemarchand 2010).

At this point it is important to consider that during the analyzed period, the number of journals and consequently the total number of published articles included within the WoS database substantially grew. 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. That study presents evidence that during the whole twentieth century, this growth phenomenon appears to show a system that is self-organizing and in equilibrium with a 0.032 growth constant. Considering that the WoS database only includes a small fraction of all the new journals, the database growth rate would be even smaller than the one estimated by Mabe (2003). The values of the ρ-growth constants presented in Table 2.2 clearly show that $\rho > 0.032$ (with the exception of Jamaica and Guyana). Consequently, the productivity of scientific articles, published by the countries of our sample during the last 48 years, still experiences exponential growth ($\rho - 0.032 > 0$).

Mabe (2003) also analyzed the high coincidence between journal growth rates and world scientist growth rates over the last 50 years $\left(\gamma_{scie} \approx 0.03\right)$. According to

that study, the phenomenon causing the increase in journal growth is the rise in the number of scientists. That hypothesis is consistent with the results of Table 2.2, and with the fact that recent growth rates for the number of scientists in Latin America have been well above the world average (Lemarchand 2010, p. 56). The rates for Spain and Portugal were even higher (see Fig. 2.2).

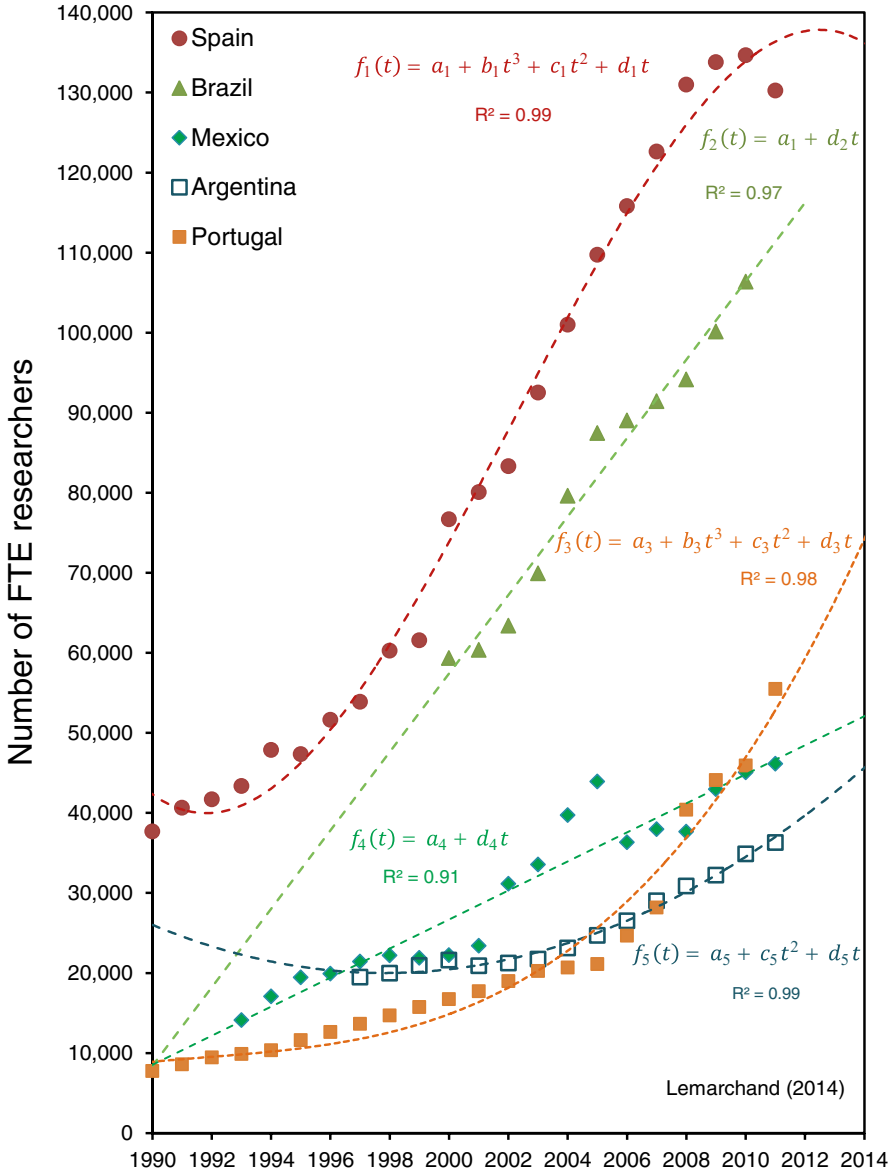

Fig. 2.2 Evolution of the number of FTE researchers (1990–2012) for Argentina (quadratic growth), Brazil (linear growth), Mexico (linear growth), Portugal (cubic growth), and Spain (cubic growth)

Since the early days of scientometrics, it has been suggested that a correlation exists between the total number of publications and national GDP (De Solla Price 1986). A recent study showed a high correlation between the number of publications over a 10-year period within the different regions of the world (Africa, Arab states, Asia-Pacific, Europe, North America, and Latin America and the Caribbean) and the shares of global GDP within the same regions (Lemarchand 2010, 2012). This correlation is tested here by analyzing the number of publications in relation to national GDP per capita expressed in constant 2005 USD over time (1966–2012). Table 2.2 shows these results. Only 57 % of the 30 countries analyzed present a high correlation $(R^2 > 0.8)$. At this point, it is not possible to generalize the hypothesis that GDP is the only driver for scientific publications. However, these results are still consistent with previous findings (Lemarchand 2012).

2.2 Ibero-American Self-organizing Co-authorship Networks (1973–2013)

Co-authorship is one of the most tangible and well-documented forms of scientific collaboration. In a recent study, Lemarchand (2012) showed that 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. In that study, a mathematical model was developed to study the temporal evolution of co-authorship networks. The model shows how the number of co-publications $P_k^i(t)$ between country k and country i, against the coupling growth coefficients a_k^i, follow a power law mathematical relation.

To show that the number of co-publications among countries also grows quadratically against time, Lemarchand (2012) assumed a linear growth for the national scientific network and a preferential attachment strategy for co-publications. The quadratic growth constants for 352 different co-authorship networks were empirically determined for the period 1973–2006 for a group of 12 Ibero-American countries (responsible for 98 % of the total regional publications between 1973 and 2010) with a group of 46 other different nations.

The developed model predicted that the connectivity of Ibero-American countries with larger scientific networks (hubs) is growing faster than that of other less connected countries. Lemarchand (2012) determined that 70.4 % of the 352 analyzed 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 published between 1973 and 2006 by the 12 countries in that sample. The rest of the co-authorship networks (smaller ones) accounted for only 8.8 % of the total regional production; Spain accounted for 6.1 %.

Lemarchand (2012) was also able to determine the dates, t_0, at which the co-authorship connectivities trigger the self-organizing scale-free network for each of the 352 cases. It was found that the latter follows a normal distribution around year 1981.4 ± 2.2, and this effect was associated with a brain-drain process generated within Ibero-American countries during the previous decade. The examined data

showed a time lag of approximately 15 years, between the peak when most Ibero-American populations were living under dictatorships (massive brain drain) and the peak when most of the co-authorship networks were triggered. Emigrant scientists living abroad need a period of time to develop a wide range of S&T human capital assets, to enhance R&D 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, emigrant scientists become "visible" to the scientific networks of their homeland. After this time lag, they may be in a position to transfer part of their accumulated knowledge and experience to their home country, via periodic visits and participating in knowledge and co-authorship networks. In this way, the preferential attachment links are enhanced and the self-organizing behavior triggered.

Based on the mathematical properties of the model, Lemarchand (2012) was able to 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. These predictions for the period 2007–2010 were tested within the 352 networks.

2.3 A Generalization of the Self-organizing Model of Scientific Networks

The original model developed by Lemarchand (2012) assumed that new researchers join the national scientific network (nodes) following a linear growth process described by the following equation $f_i(t) = d_i t + a_i$. Here, $f_i(t)$ represents the total number of nodes for country i, d_i the growth constant, and a_i the total number of nodes when $t = 0$. The model has the following assumptions: (a) nodes join the network in a linear way $(f_i(t))$; (b) incoming nodes link to already present nodes following preferential attachment; and (c) nodes already present in the network form new internal links following preferential attachment. Lemarchand (2012) defined $P_i(t)$ as the number of links (co-publications) at time t and country i. Thus, it is possible to show that the number of co-publications among pairs of countries over time follows the following equation:

$$P_i(t) = \alpha\left[t - t_0\right]^2 + \gamma \tag{2.1}$$

Here, α is the growth constant, t_o is the time at which the system becomes self-organized, and γ is the minimum number of co-publications, which triggers the self-organizing process. The three constants (α, γ and t_o) can be empirically determined.

Because in the majority of countries the national scientific network grows linearly, the model worked extraordinary well for almost all nations, but there were some exceptions (i.e., China and India).

To generalize the model (Lemarchand and Barrera-Lemarchand 2016), no special assumptions were made regarding the type of mathematical functions for $f_i(t)$. The mathematical functions of $f_i(t)$ are: (1) constant $(f_i(t) = a_i)$; (2) linear $(f_i(t) = d_i t + a_i)$; (3) quadratic $(f_i(t) = c_i t^2 + d_i t + a_i)$; or (4) cubic $(f_i(t) = b_i t^3 + c_i t^2 + d_i t + a_i)$.

Consequently, the dynamics placed by the preferential attachment effect will induce a different set of mathematical functions for $P_i(t)$. If $f_i(t)$ is constant, then $P_i(t)$ will have a linear growth; if $f_i(t)$ is linear, then $P_i(t)$ will be quadratic; if $f_i(t)$ is quadratic, then $P_i(t)$ will be cubic; and if $f_i(t)$ is cubic then $P_i(t)$ will be quartic.

The behavior of the national scientific networks can be analyzed by studying the number of scientists in a particular nation. Figure 2.2 shows the long-term behavior of the number of FTE researchers between 1990 and 2012 for the five most productive Ibero-American countries. The definition of FTE researchers follows the one proposed by the Frascati Manual (OECD, 2002). The raw data were provided by the UNESCO Institute for Statistics.

The evolution of FTE researchers constitutes the national scientific network $f_i(t)$, where $i = 1$ (Spain), $i = 2$ (Brazil), $i = 3$ (Portugal), $i = 4$ (Mexico), and $i = 5$ (Argentina). To test the model, the behavior of 25 scientific networks was analyzed using data covering 41 years.

Figures 2.3, 2.4, 2.5, 2.6 and 2.7 show the evolution (1973–2013) of the number of scientific co-publications between the five countries of this sample (Spain, Brazil, Portugal, Mexico, and Argentina) with their five main scientific partners. The quadratic, cubic, or quartic fitting curves are in total agreement with the predictions made by the generalized model described here, improving the results obtained in Lemarchand (2012).

The values obtained for the determination coefficients (R^2) between the number of co-publications and the curves predicted by this model show that in 72 % of cases, $R^2 > 0.99$, in 16 %, $R^2 > 0.98$, in 8 %, $R^2 > 0.97$, and within the remaining 4 %, $R^2 > 0.96$. These are extraordinary results taking into account that this analysis covers the social behavior of co-publications among 25 different pairs of countries in a 41-year period.

2.4 Conclusions

This study analyzed the long-term evolution of scientific articles published in mainstream journals over a period of 48 years. The focus was on all Ibero-American and Caribbean countries. Within this period, the ten most productive Ibero-American and Caribbean countries accounted for 97 % of all publications, the 15 most productive for 99 % and the 30 most productive countries for 99.9 %.

The analysis also included the estimation of the various ranking positions of the top 10 Ibero-American within the world ranking since 1970 (see Table 2.1). Spain, Brazil, Colombia, and Portugal showed the most dramatic ranking improvements, whereas Venezuela, Argentina, and Chile had the greatest falls.

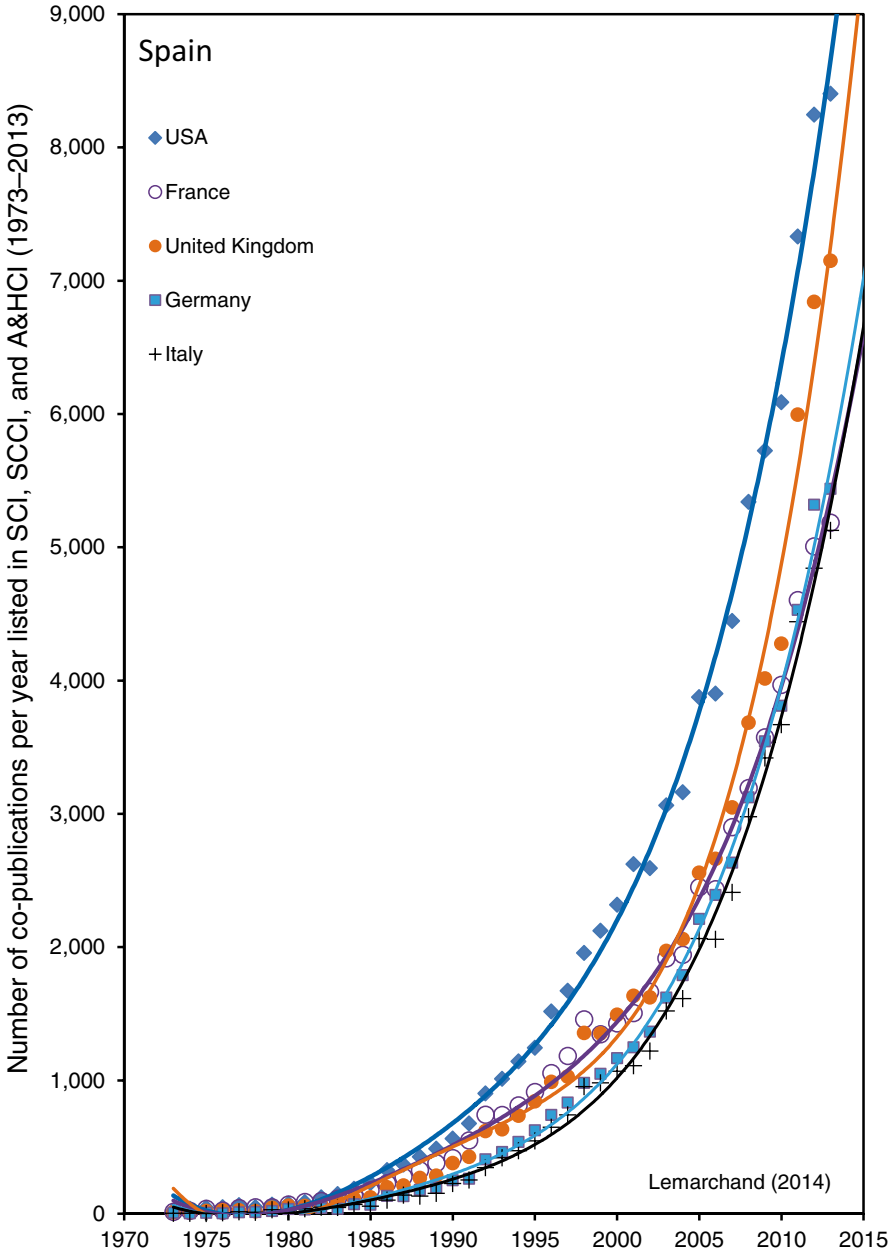

Fig. 2.3 Temporal evolution (1973–2013) of the co-authorship social network for Spain; the model predicts a quartic growth in the number of links (publications) over time because the FTE researchers in Spain shows cubic growth (the *solid lines* represent the quartic fit)

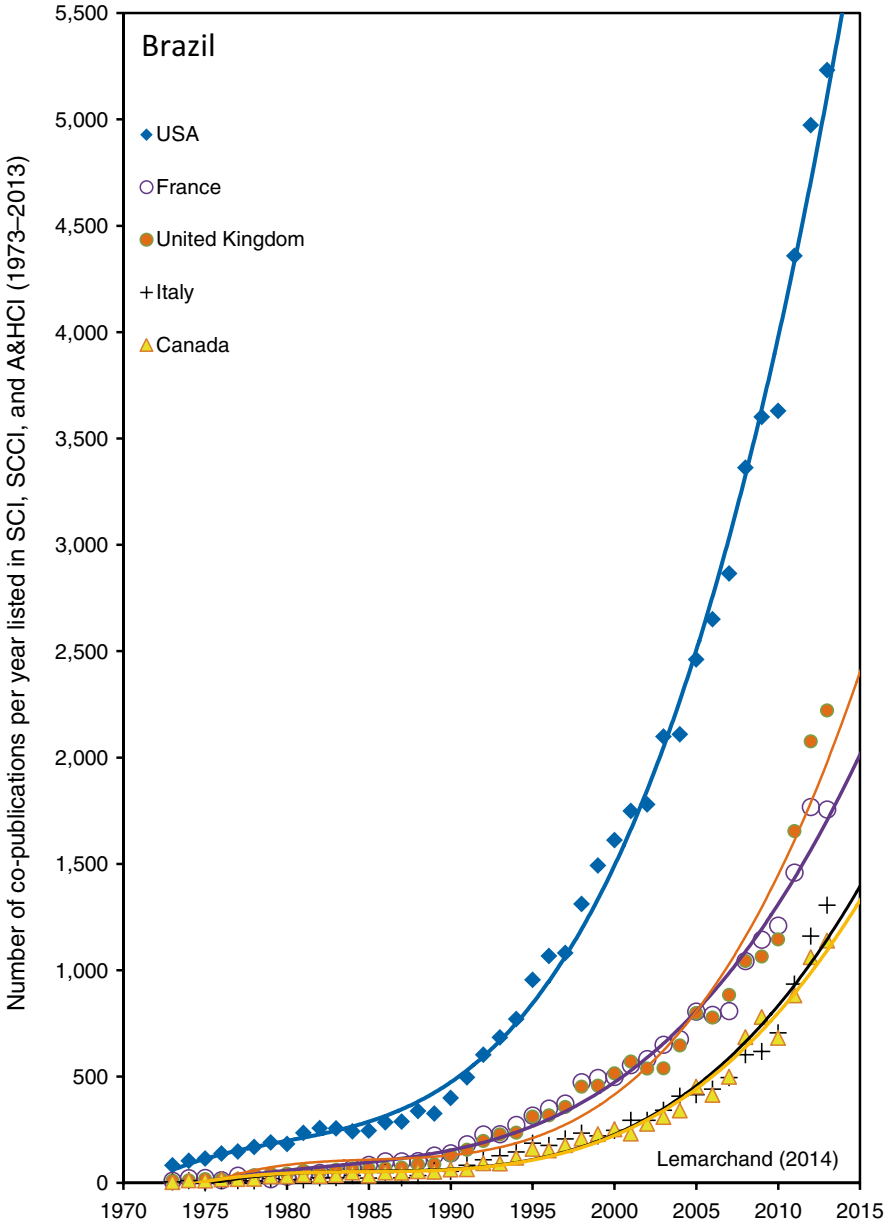

Fig. 2.4 Temporal evolution (1973–2013) of the co-authorship social network for Brazil; the model developed predicts a parabolic growth in the number of links (publications) over time (the *solid lines* represent the quadratic fit)

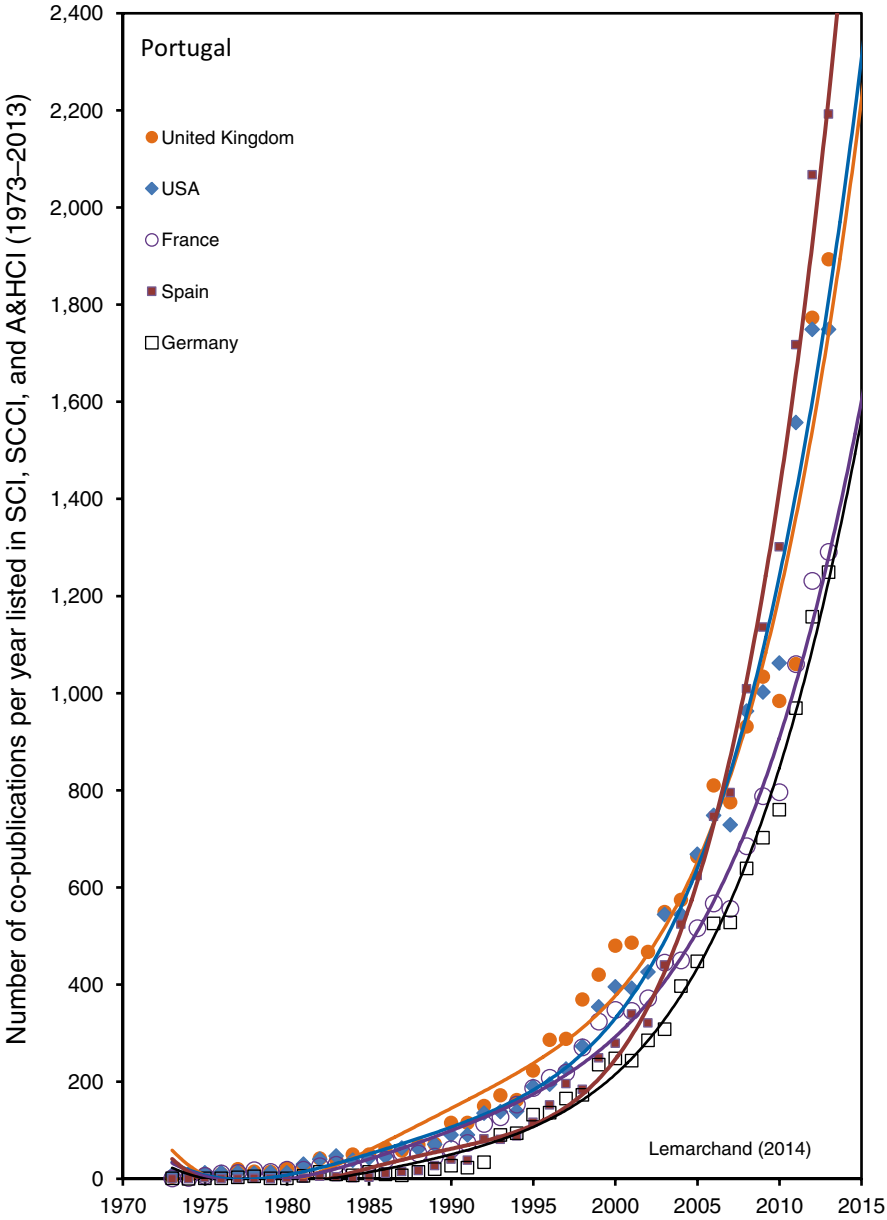

Fig. 2.5 Temporal evolution (1973–2010) of the co-authorship social network for Portugal; the model developed predicts a quartic growth in the number of links (publications) over time because the number of FTE researchers shows cubic growth (the *solid lines* represent the quartic fit)

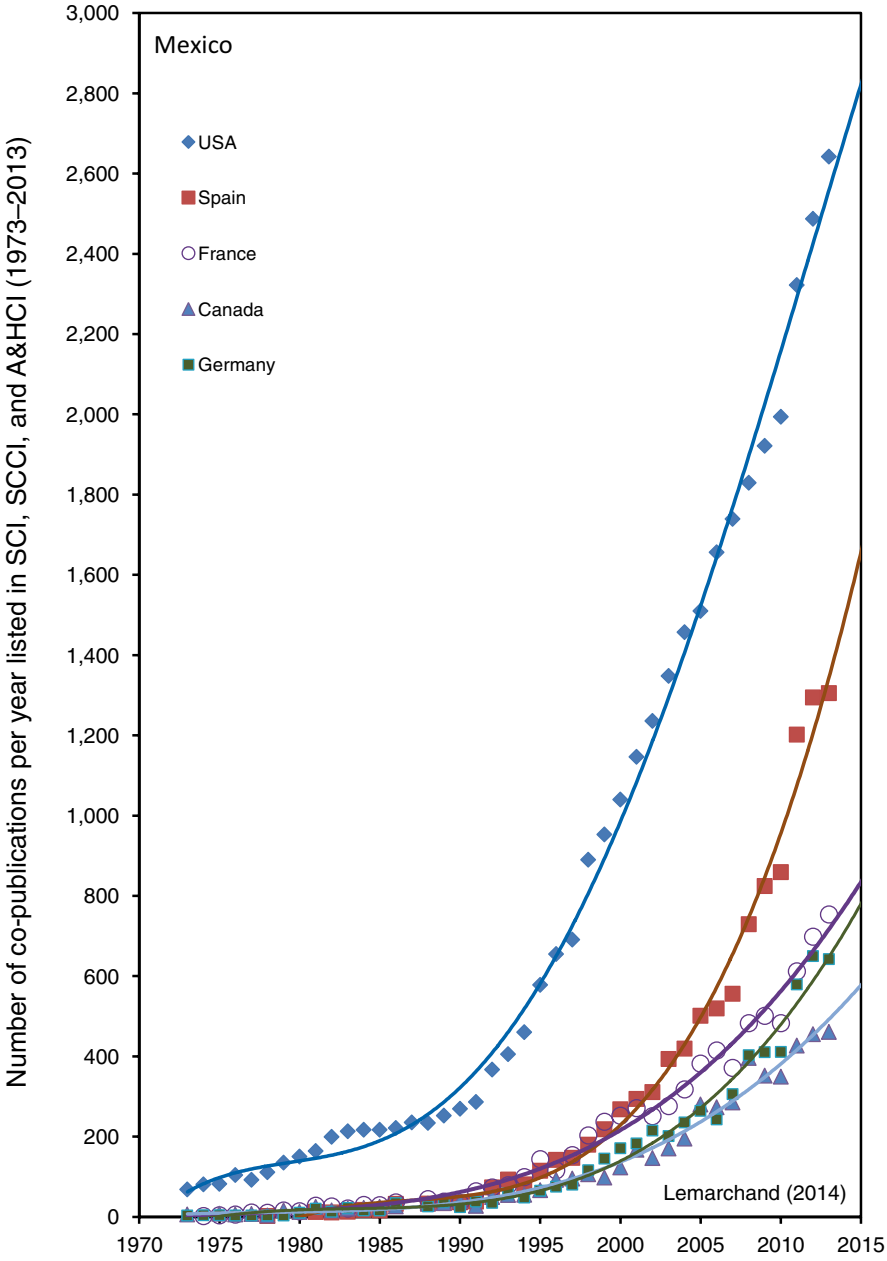

Fig. 2.6 Temporal evolution (1973–2013) of the co-authorship social network for Mexico; the model developed predicts a parabolic growth in the number of links (publications) over time (the *solid lines* represent the quadratic fit)

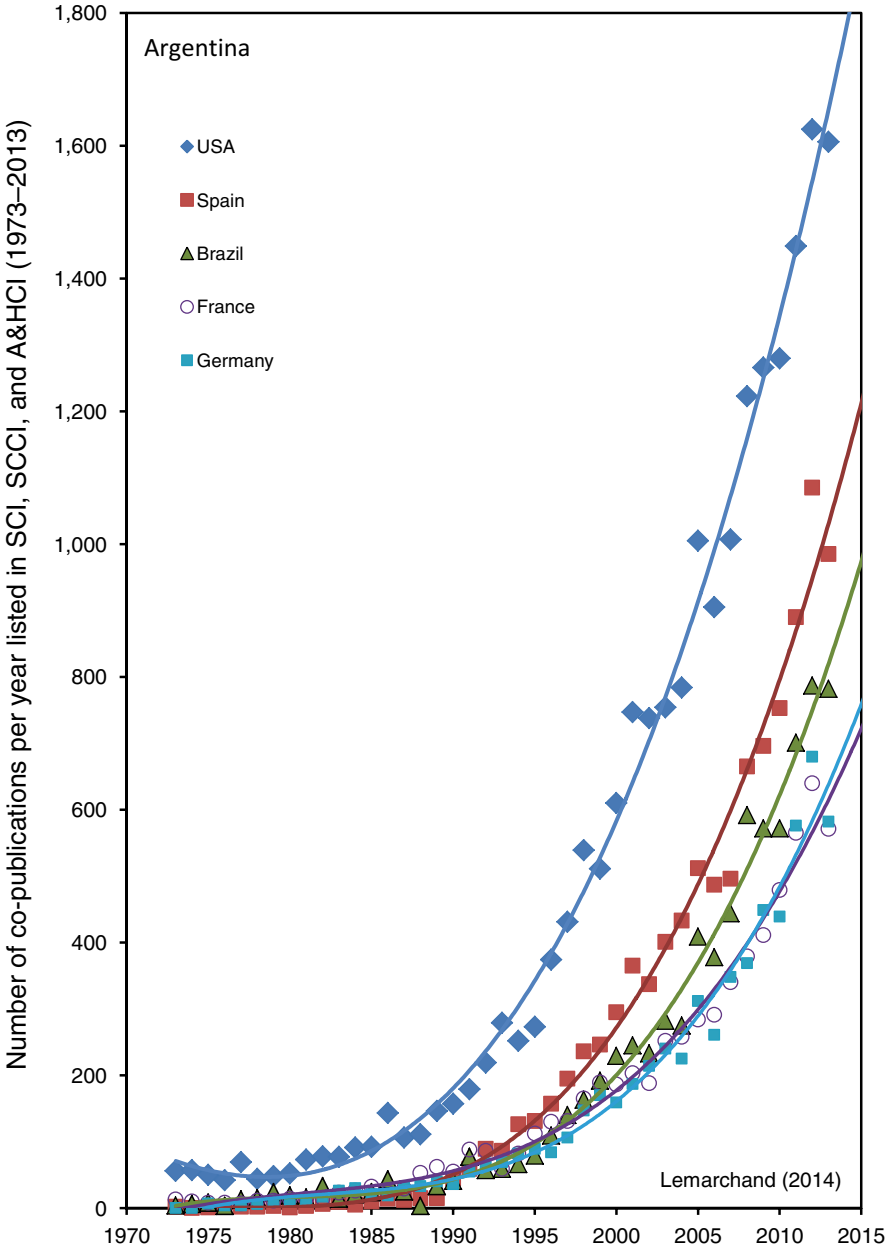

Fig. 2.7 Temporal evolution (1973–2013) of the co-authorship social network of Argentina; the model developed predicts a cubic growth in the number of links (publications) over time because the number of FTE researchers shows quadratic growth (the *solid lines* represent the cubic fit)

Participation in publication was also estimated, for 30 countries in three different periods (see Table 2.2). The last decade was extraordinarily productive, accounting for 59 % of all publications produced in the last 48 years.

The long-term growth (1966–2013) of scientific articles in mainstream journals for 18 Ibero-American countries was represented, accounting for 99.4 % of all publications (see Fig. 2.1). This analysis enabled the observation of slope changes, which may relate to modifications to national science, technology, and innovation ecosystems, or with the application of new public policies (Lemarchand 2010, 2012). In some cases productivity increased while in others the new policies failed and consequently productivity diminished.

The growth-rate constants for 30 countries were determined for three categories: (a) number of publications; (b) number of publications per million inhabitants; and (c) ratio of the number of publications and GDP per capita. In all three categories, Portugal showed the highest growth rates with determination coefficients $R^2 > 0.99$.

Furthermore, the characteristics of the self-organizing model of co-authorship networks (Lemarchand 2012) were analyzed. To ensure generalization, no limits were placed on the evolution of the national scientific networks over time. By representing the long-term evolution of the number of FTE researchers for Spain, Brazil, Portugal, Mexico, and Argentina (see Fig. 2.2) the type of mathematical function that describes the evolution of each national scientific network $(f_i(t))$ could be determined. With that information, it was possible to predict the mathematical behavior of the number of co-publications among pair of countries $(P_i(t))$. This model was tested against 25 different scientific networks using data between 1973 and 2013 and showed that 100 % of the determination coefficients had values $R^2 > 0.96$ while 72 % had values $R^2 > 0.99$.

The results obtained in this study are remarkable, especially taking into account that the variable described in this model is associated with co-authorship behaviors among groups of individual scientists working in different countries, with different environments and levels of political stability, over a period of 41 years.

The reliability of the original and generalized model of self-organizing scientific networks enables their application for foresight studies and for the design of specific research and innovation policy instruments.

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