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Allometric models to measure and analyze the evolution of international research collaboration

Mario Coccia[1,2] · **Barry Bozeman**[2]

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Abstract A fundamental problem in the field of the social studies of science is how to measure the patterns of international scientific collaboration to analyse the structure and evolution of scientific fields. This study here confronts the problem by developing an allometric model of morphological changes in order to measure and analyse the *relative growth* of international research collaboration in comparison with domestic collaboration only for fields of science. Statistical analysis, based on data of internationally co-authored papers from National Science Foundation (1997–2012 period), shows an acceleration (a disproportionate relative growth) of collaboration patterns in medical sciences, social sciences, geosciences, agricultural sciences, and psychology (predominantly applied fields). By contrast, some predominantly basic fields, including physics and mathematics, have lower levels of relative growth in international scientific collaboration. These characteristics of patterns of international research collaboration seem to be vital contributing factors for the evolution of the social dynamics and social construction of science. The main aim of this article is therefore to clarify the on-going evolution of scientific fields that might be driven by the *plexus* (interwoven combination of parts in a system) of research disciplines, which generates emerging research fields with high growth rates of international scientific collaboration.

Keywords International research collaboration · Evolution of science · Dynamics of science · Measuring evolution of research fields · Scientific fields · Applied research · Basic research · Allometry

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✉ Mario Coccia
mario.coccia@ircres.cnr.it

Barry Bozeman
bbozeman@asu.edu

[1] Ircres, CNR - National Research Council of Italy, Via Real Collegio, 30-10024 Moncalieri, Torino, Italy

[2] School of Public Affairs, Arizona State University, Phoenix, AZ, USA

Problem and conceptual grounding

International research collaboration plays a vital role in the social construction of science (Zitt et al. 2000; Laudel 2002; Kim 2006; Luukkonen et al. 1993; Bozeman and Corley 2004; Hackett et al. 2008; Bozeman et al. 2015; Youtie and Bozeman 2014). One reason, research collaboration has received much attention by scholars because it is one of the social processes that help shape the evolution of research fields (De Solla 1963; de Solla Price and Beaver 1966; Beaver de and Rosen 1978; Frame and Carpenter 1979; Luukkonen et al. 1992; Coccia and Wang 2016). Laudel (2001, 2002) claims that scientific collaboration is based on different elements, such as mutual sharing of knowledge and data, and mutual intellectual stimulation among the collaborators (cf., Youtie and Bozeman 2014; Bozeman et al. 2013). Laudel (2001) also shows that most scientific collaborations begin with face-to-face meetings in facilitative environments (e.g., conferences, congresses and research groups). Research collaboration is also important because it fosters a rational division of scientific labour to increase the efficiency of production processes and accelerating the time needed for achieving fruitful results/discoveries (cf. Lee and Bozeman 2005; Coccia 2004, 2005, 2008b; Coccia et al. 2015; Crow and Bozeman 1998). Overall, collaborations in science can better support breakthroughs by sharing knowledge, data, skills, techniques, equipment, and facilities (Coccia 2014b; Coccia and Wang 2016).

De Solla Price's (1963) pioneering work measured collaborations by using multi-authored articles. Lundberg et al. (2006) argue that co-authorship is still the most useful and efficient scientific indicator for measuring and evaluating collaboration patterns. The analyses of co-authorship with different approaches and techniques of bibliometrics and scientometrics have showed main differences of scientific production and citations of joint articles across countries and/or research fields (cf. Egghe 1991; van Raan 1998; Acedo et al. 2006; Coccia 2007; Coccia et al. 2015; Coccia and Wang 2016). However, one main problem is *how* to accurately measure and analyse the growth of the patterns of international scientific collaboration among research fields.

In particular, why are the measurement and analysis of growth patterns in international research collaboration important? *In the first place*, international collaboration has long been viewed as a means for the diffusion of knowledge, craft and technique as the researchers from one nation learn about the approaches of researchers in other nations (for an overview of the research on knowledge and skills diffusion, *see* Mitton et al. 2007; Peterson 2009; Coccia 2014a). *Second*, some feel that international research collaboration is a proxy for the attractiveness and robustness of a scientific field, an indicator that it is not a backwater enterprise or a field dominated by parochial interest (Wagner 2008; de Solla Price and Beaver 1966). *Third*, some contend that international research collaboration is a leading indicator of other beneficial forms of cooperation among nations, including commercial exchange and even political alliance (cf. Luukkonen et al. 1992). *Fourth,* the growth of collaboration patterns of research fields can explain some properties of the evolution of science for understanding the social construction of science and for supporting efficient research policies of governments (cf., Frame and Carpenter 1979; Luukkonen et al. 1992; Lee and Bozeman 2005; Coccia and Wang 2016; Bozeman and Youtie 2016).

During the recent decades, several studies have showed the high levels of volume, velocity, and variety of international and domestic co-authored papers in all scientific fields (cf. Luukkonen et al. 1992; Laudel 2001; Puuska et al. 2014), but questions remain about the contemporary dynamics of growth of international research collaboration nested in the evolution of scientific fields. In fact, patterns of international research collaboration are not static but dynamic (change from one time to another) and an accurate measurement of collaboration patterns for fields of science is important for policy makers, though it is a problematic topic due to changing frontiers of research fields during the continuos evolution of science.

In light of the continuing importance of the internationalization of research collaboration, our study seeks to measure and analyse patterns of international research collaboration to shed some empirical light on recent trends of the "social dynamics of science" (Sun et al. 2013). We focus specifically on the following questions:

(a) How do research fields grow and evolve with respect to international research collaboration?
(b) Which disciplines and scientific fields have accelerated the evolutionary growth of international research collaboration? And why?

The current study confronts these issues here by applying an analytical framework to measure, analyse and explain the magnitude of international scientific collaboration across research fields over time. In particular, the purpose of the present study is to measure and analyse scientific discipline's relative growth of internationally co-authored articles in comparison to domestic ones only. We examine allometric growth of scientific research collaboration for fields of science. The focus in allometry is tracking and understanding disproportionate growth of a component compared to overall body or population. This analysis is based on a model used rarely in the social sciences but more often in the natural sciences. In fact, most studies of allometric growth today are in fields related to biology (e.g., Lleonart et al. 2000), but especially biological components of ecology (e.g., Weiner and Thomas 1992; Ong et al. 2004). In the social sciences the use of allometry concepts and measures has been quite uncommon but has understandably included demographic and population studies, especially studies of urban sprawl (Cheng and Masser 2004; Batty and Kim 1992), as well as studies of spatial patterns of economic growth (Coccia 2009c). To the extent we have been able to determine, fewer than 20 studies in all social sciences have used allometric functions for analysis, and only a single study in science studies or economics of innovation: Sahal's (1981) study of the spatial diffusion of technological innovation. In light of the lack of studies in our field of inquiry, the allometric approach can provide quantitative features and characteristics of the current evolution of international research collaboration across scientific fields, more and more important for understanding the social construction and social dynamics of science, and supporting fruitful research policies. We provide in "Methodology" section below a modest history of the concept of allometry and its meanings and applications. First, however, we discuss the data, materials and methods.

Data and study design

This study focuses on institutional collaboration in different scientific fields based on article counts from the set of journals covered by the Science Citation Index (SCI) and Social Sciences Citation Index (SSCI). In particular, this study uses the dataset by the National Science Foundation (2014), the National Center for Science and Engineering Statistics, which includes special tabulations from Thomson Reuters, SCI and SSCI. The study design considers articles in all fields combined by co-authorship attribute (total articles with domestic institutions only and total articles with international institutions) for selected nations during the 1997–2012 period. Articles are assigned to a country on the basis of the institutional address(es) listed in the article. Articles are credited on a whole-count basis (i.e., each collaborating country is credited with one count). Countries included in the analysis are all those with more than 1 % of internationally co-authored articles in 2012. Articles with multiple institutions are counts of articles with two or more institutional addresses. Articles with domestic institutions only are counts of articles with one or more institutional addresses all within the country, whereas articles with international institutions are counts of articles with one or more institutional addresses outside the country. The forty countries of the sample are listed in Appendix 1, whereas the research fields are described in Appendix 2. About 97 % of the worldwide production of articles (1997–2012 period) was produced by the sample of forty countries described in Appendix 1.

To reiterate, the purpose of the present study is therefore to measure and analyse scientific discipline's relative growth of internationally co-authored articles in comparison to domestic ones only. The results clarify, whenever possible some properties and characteristics of the evolution of scientific fields over time. We now move on to present the analytical method for analysing and explaining the on-going evolution of international scientific collaboration for fields of science.

Methodology: allometry and model of morphological changes for measuring patterns of international scientific collaboration

We suppose that external factors to science (such as Information and Communications Technologies) are accelerating the volume, velocity and variety of international and domestic research collaboration across all scientific fields (cf., Luukkonen et al. 1992). In order to measure and analyse the evolutionary growth of international institutional co-authorships in comparison to domestic ones only for fields of science, we employ a mathematical model of morphological change (Sahal 1981; Coccia 2009c; cf. also Coccia 2009d). The crux of the model is rooted in allometry and since this approach is uncommon in the social sciences some brief backgrounds is useful to understand and clarify it.

Allometry and allometric growth in science

More many decades biologists have sought to understand and to develop models for morphological changes in organisms (e.g., Huxley 1932; Reeve and Huxley 1945). As Gayon (2000) notes, the general curve fitting approach now referred to as allometry preceded Julian Huxley's and Georges Teissier's clarification and naming of the term in 1936. Allometry is a formula for a "law of constraint differential growth" used as early as 1900 by not only Huxley but also Dubois and Lapicque for a power law and for logarithmic coordinates relating mammalian brain size to body size. For decades after, allometry proved central to evolutionary theory, especially paleobiology (Gayon 2000).

After early work in evolution, allometry was expanded to many other applications in biology and ecology, most having to do with scale effects (e.g., wing and flight performance). Soon it became evident that allometry and allometric curves could prove useful for any set of co-varying measures and the approach proved especially useful for understanding scale effects in explosive growth in one set of measures *vis-a-vis* another. Indeed, the term "allometry" means literally "different measure" and focuses on the growth of a component at an accelerated rate compared to the overall body or population. Allometries may be linear, non-linear, log functions or, indeed, follow almost any scale relationship. Allometric measures are employed for a variety of relational patterns, including traits measured through time (ontogenetic allometry), developments within a fixed stage of a population (static allometry) and growth differences among species—evolutionary allometry (see Niklas 1994 for an overview).

As mentioned, one of the first uses of allometry in the social sciences was by Sahal (1979, 1981) who used allometric measures to understand technological diffusion of innovations. Specifically, Sahal (1981, pp. 77–98) used allometry to model spatial diffusion and substitute effects for a variety of technologies, including electricity generation, steel production, farm tractors, digital computers, tank ship, locomotive, aircraft, etc. He found that technological substitution occurs with a change rate in which the innovation reaches a threshold at where the new technology grows explosively in a disproportionate growth pattern. Coccia (2009c) applied the allometric approach to measure and analyze the different patterns of regional economic growth in Italy. Our allometric model explains the patterns of international research collaboration by using Sahal's approach (1981).

The allometric model for measuring and analyzing the evolution of international scientific collaboration for fields of science

The equations and notations here are similar to spatial model of technological substitution by Sahal (1981, pp. 82–90). *Suppose* that let $X(t)$ be the extent of international collaboration of a scientific field i at the time t and $Y(t)$ be the extent of domestic collaboration of the scientific field i at the same time. Both Y and X increase with S-shaped patterns of growth.

One way to represent, analytically, the pattern of Y is in terms of the differential equation of the logistic function:

$$\frac{1}{Y}\frac{\mathrm{d}Y}{\mathrm{d}t} = \frac{b_1}{K_1}(K_1 - Y)$$

We can rewrite the equation as:

$$\frac{K_1}{Y}\frac{1}{(K_1 - Y)}\mathrm{d}Y = b_1\mathrm{d}t$$

with K_1 = equilibrium level of growth, and b_1 = rate-of-growth parameter.

The integral of this equation is:

$$\log Y - \log(K_1 - Y) = A + b_1 t$$

then, $\log\frac{K_1 - Y}{Y} = a_1 - b_1 t$ (note that a_1 is constant depending on the initial conditions) whence,

$$Y = \frac{K_1}{1 + \exp(a_1 - b_1 t)}$$

$a_1 = b_1 t$, and t = abscissa of the point of inflection. In particular, the logistic curve is a symmetrical S-shaped curve with a point of inflection at 0.5 K.

Hence, the growth of Y can be described respectively as:

$$\log\frac{K_1 - Y}{Y} = a_1 - b_1 t \qquad (1)$$

Mutatis mutandis, the equation of the growth of X is given by:

$$\log \frac{K_2 - X}{X} = a_2 - b_2 t \tag{2}$$

Solving Eqs. (1) and (2) for t, the result is:

$$t = \frac{a_1}{b_1} - \frac{1}{b_1} \log \frac{K_1 - Y}{Y} = \frac{a_2}{b_2} - \frac{1}{b_2} \log \frac{K_2 - X}{X}$$

The expression generated is:

$$\frac{Y}{K_1 - Y} = C_1 \left(\frac{X}{K_2 - X} \right)^{\frac{b_1}{b_2}} \tag{3}$$

$$C_1 = \exp\left(\frac{a_2 b_1 - a_1 b_2}{b_2} \right)$$

When X and Y are small in comparison with their final value, then Eq. (3) is:

$$\frac{Y}{K_1} = C_1 \left(\frac{X}{K_2} \right)^{\frac{b_1}{b_2}}$$

Hence, the following simple model of growth is obtained:

$$X = A_1 (Y)^{B_1} \tag{4}$$

where $A_1 = \frac{K_2}{(K_1)^{\frac{b_2}{b_1}}} C_1$ and $B_1 = \frac{b_2}{b_1}$; B_1 is the allometry exponent.

The logarithmic form of the equation $X = A_1 (Y)^{B_1}$ is a simple linear relationship:

$$LnX = LnA_1 + B_1 LnY$$

The value of B_1 indicates different patterns of growth; in particular, if the relative growth of the two dimensions were *isometric* (i.e., with the same growth), the allometry exponent B_1 should have a unit value:

$$B_1 = 1$$

whether X increases at greater relative rate than Y, the *positive allometric growth* can be expressed as:

$$B_1 > 1$$

Instead, whether X has a negative allometric growth relatively to Y, then:

$$B_1 < 1$$

To analyse the patterns of international research collaboration, the present study examines articles by their co-authorship attribute (domestic and international research collaboration) during the time period $t = 1997$–2012 for several scientific fields i ($i =$ Astronomy, Physics, Geosciences, Mathematics, Computer Sciences, Biological Sciences, Psychology, Medical Sciences, Other Life Sciences, Chemistry, Engineering, Agricultural Sciences, and Social Sciences). Data are transformed in natural logarithmic values to apply the model mentioned.

In particular, model (4) can explain the growth patterns of international scientific collaboration in different research fields in relation to domestic research collaboration only, at the same time period.

The specification of the model (4) in our study is given by:

$$x_{i,t} = a \cdot (y_{i,t})^{B} \tag{5}$$

where a is a constant; $x_{i,t}$ will be the extent of internationally co-authored articles in the research field i at time t (1997–2012); $y_{i,t}$ will be the extent of domestic institutional co-authorships in the research field i at time t; $y_{i,t}$ is a driving force of international collaboration of the scientific field i.

The logarithmic transformation of the Eq. (5) is a simple linear relationship:

$$\mathrm{Ln}\, x_{i,t} = \mathrm{Ln}\, a + B\, \mathrm{Ln}\; y_{i,t} + u_{i,t} \quad \left(\text{with } u_{i,t} = \text{error term}\right) \tag{6}$$

Eq. (6) describes, in this study, the changes in international scientific collaboration that different research fields undergo during their evolutionary pathways.

Remark: b_1 and b_2 are the growth rates of *X(t)* and *Y(t)* respectively, such that $B = \frac{b_1}{b_2}$ measures the relative growth of international collaboration *X(t)* in relation to the growth of domestic collaboration *Y(t)*.

The B value, in the study here, indicates:

- $B = 1$, both international and domestic co-authored articles in the research field i are growing at the same rate (*isometric growth of international and domestic research collaboration*);
- $B < 1$, the rate of internationally co-authored articles is growing more slowly than that of domestic co-authored articles: *negative allometric growth of international scientific collaboration*;
- $B > 1$, there is *a positive allometric growth or development of internationally co-authored articles* in the scientific production of the research field.

Model (6) has linear parameters that are estimated with the Ordinary Least-Squares Method. Considering the parameter *B,* for all research fields, the following hypothesis testing $H_0 : \hat{B} = 1$ has been applied. This test, which uses Student's t-distribution, intends to verify whether all research fields have a disproportionate growth of international scientific collaboration: hence, the expectation is that the test rejects the H_0 (i.e., B should statistically differ from 1). This result suggests a quantitative feature of the evolution of research fields: a disproportionate growth of international research collaboration compared to domestic one. In addition, the hierarchical cluster with the Squared Euclidean distance and Ward's Method linkage is also applied to detect homogenous sets of scientific disciplines that have a similar relative growth of international research collaboration. We represent in a bar graph the variety of growth rates of collaboration patterns for different fields of science (allometric coefficients), whereas the dendrogram shows the homogenous sets of disciplines based on similar relative growth rates of international collaboration. Statistical analyses are performed by using the Statistics Software SPSS.

Statistical analysis

Table 1 shows the descriptive statistics of data.

Normality of distributions of data is checked with skewness and kurtosis coefficients as well as with a *Q–Q* plot.

Firstly, the answer to the question (a) stated in "Problem and conceptual grounding" section—How research fields grow and evolve with respect to international research collaboration—is given by results in Tables 2, 3.

Table 2 shows the estimated relationships and allometric coefficients for fields of science. The significance of the coefficients and explanatory power of the models is good, except for biological sciences. R^2 values are nevertheless high and thus in a majority of cases the models explain more than 90 % variance in data.

Moreover, as shown in Table 3, one-sample *T* test allows to determine if the sample mean (of a normally distributed variable) significantly differs from the hypothesized value 1 (i.e., the isometric value: same growth of international and domestic co-authored papers).

Table 1 Descriptive statistics of co-authored articles across scientific fields. *Source*: National Science Foundation (2014)

Variables	Arithmetic mean	SD
Y ENGINEERING Domestic Research Collaboration	53,933.44	11,050.737
X ENGINEERING INTERNATIONAL Collaboration	11,879.56	4297.035
Y ASTRONOMY Domestic Research Collaboration	4486.31	334.773
X ASTRONOMY INTERNATIONAL Collaboration	4315.62	1053.922
Y CHEMISTRY Domestic Research Collaboration	74,469.81	10,589.917
X CHEMISTRY INTERNATIONAL Collaboration	15,477.88	4353.663
Y PHYSICS Domestic Research Collaboration	71,599.44	7131.693
X PHYSICS INTERNATIONAL Collaboration	25,609.31	3762.591
Y GEOSCIENCES Domestic Research Collaboration	27,220.69	3287.742
X GEOSCIENCES INTERNATIONAL Collaboration	10,504.13	3511.775
Y MATHEMATICS Domestic Research Collaboration	11,230.19	1813.394
X MATHEMATICS INTERNATIONAL Collaboration	4183.69	1149.189
Y COMPUTER SCIENCES Domestic Research Collaboration	5131.13	997.340
X COMPUTER SCIENCES INTERNATIONAL Collaboration	1620.06	630.416
Y AGRICULTURE Domestic Research Collaboration	12,515.69	1631.712
X AGRICULTURE INTERNATIONAL Collaboration	2913.13	1026.699
Y BIOLOGY Domestic Research Collaboration	119,026.19	3418.275
X BIOLOGY INTERNATIONAL Collaboration	34,379.38	6865.521
Y MEDICINE Domestic Research Collaboration	137,247.38	7037.091
X MEDICINE INTERNATIONAL Collaboration	28,201.06	8191.414
Y OTHER LIFE SCIENCES Domestic Research Collaboration	6287.25	1677.013
X OTHER LIFE SCIENCES INTERNATIONAL Collaboration	784.38	524.110
Y PSYCHOLOGY Domestic Research Collaboration	15,138.94	2484.027
X PSYCHOLOGY INTERNATIONAL Collaboration	2615.56	1281.085

Note In this study *Y* is the explanatory variable, whereas *X* is the dependent variable; Research fields are: Astronomy, Physics, Geosciences, Mathematics, Computer Sciences, Biological Sciences, Psychology, Medical Sciences, Other Life Sciences, Chemistry, Engineering, Agricultural Sciences, and Social Sciences. *SD* is Standard Deviation

Table 2 Scientific field regressions of allometric equation

Research fields	Constant α (SE)	Allometric coefficient $\beta = B$ (SE)	R^2 (SE of the estimate)	F (sign.)
Dependent variable: LN Internationally co-authored papers with international institutions at $t = 1997, \ldots, 2012$				
Astronomy	−8.227 (6.062)	1.971** (0.721)	0.301 (0.209)	7.470 (0.016)
Physics	−5.444** (1.750)	1.395*** (0.157)	0.839 (0.060)	79.355 (0.00)
Geosciences	−18.994*** (1.931)	2.763*** (0.189)	0.934 (0.089)	213.278 (0.00)
Mathematics	−7.980*** (0.974)	1.748*** (0.105)	0.949 (0.068)	279.332 (0.00)
Computer Sciences	−8.393*** (1.049)	1.843*** (0.123)	0.937 (0.095)	224.581 (0.00)
Biological Sciences	−7.573 (21.932)	1.540 (1.877)	−0.022 (0.207)	0.673 (0.426)
Psychology	−20.313*** (2.519)	2.920*** (0.262)	0.891 (0.161)	124.157 (0.00)
Medical Sciences	−48.022*** (9.855)	4.923*** (0.833)	0.693 (0.165)	34.909 (0.00)
Other Life Sciences	−16.066*** (1.939)	2.583*** (0.222)	0.899 (0.226)	134.868 (0.00)
Chemistry	−12.138*** (0.961)	1.940*** (0.086)	0.972 (0.047)	512.476 (0.00)
Engineering	−10.206*** (0.752)	1.795*** (0.069)	0.978 (0.056)	674.651 (0.00)
Agricultural Sciences	−17.785*** (1.592)	2.726*** (0.169)	0.945 (0.086)	260.561 (0.00)
Social Sciences	−17.074*** (1.814)	2.517*** (0.181)	0.927 (0.130)	192.517 (0.00)

Note Explanatory variable is LN co-authored articles with domestic institutions only; $t = (1997–2012)$. *SE* is Standard Error

*** Coefficient β is significant at 1 ‰

** Coefficient β is significant at 5 %

Table 3 One sample *T* test

Descriptive statistics for all research fields

	N	Mean	SD	SE mean
Allometric coefficient *B*	12	2.427	0.925	0.267

One-sample test Test value = 1

					95 % confidence interval of the difference	
	t	*df*	Sig.	Mean difference	Lower	Upper
Allometric coefficient *B*	5.342	11	0.001	1.427	0.839	2.015

Note SD Standard Deviation; *SE* Standard Error

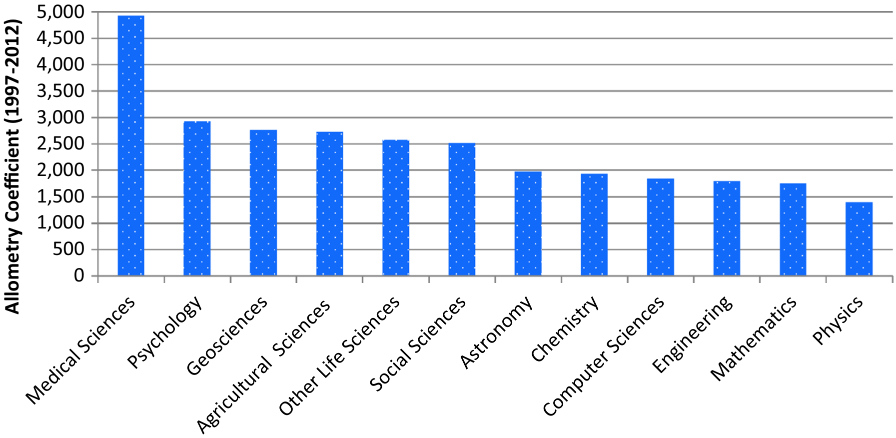

Fig. 1 Allometric coefficients of growth of international scientific collaboration across scientific fields over 1997–2012. *Note* Allometric coefficients are from estimated values of Table 2. Biological sciences do not have significant values and are not represented in Fig. 1

In particular, the arithmetic mean of the internationally co-authored papers across scientific fields is 2.427 (in logarithmic value), which is statistically and significantly different from the test value of 1 (p <0.001 in Table 3). This result shows that international scientific collaboration of scientific disciplines has a disproportionate growth in relation to domestic co-authored papers over time ($p < 0.001$). Hence, international scientific collaboration among research fields has a general disproportionate growth compared to domestic collaboration only (Table 2, 3). However, *B* values have a diversity and specificity between different scientific disciplines as shown in Fig. 1.

Secondly, the answer to the question (b) stated in introduction—Which scientific fields have accelerated the growth of international research collaboration—is explained by the results of statistical analyses as follows.

Especially, Fig. 1 shows different allometric coefficients *B* for fields of science (estimated in Table 2). The highest relative growth rate of internationally co-authored papers is in medical sciences, whereas the lowest relative growth rate is in physics and mathematics over 1997–2012 (the field of biological sciences is not represented in Fig. 1 because the *B* value is not significant in Table 2).

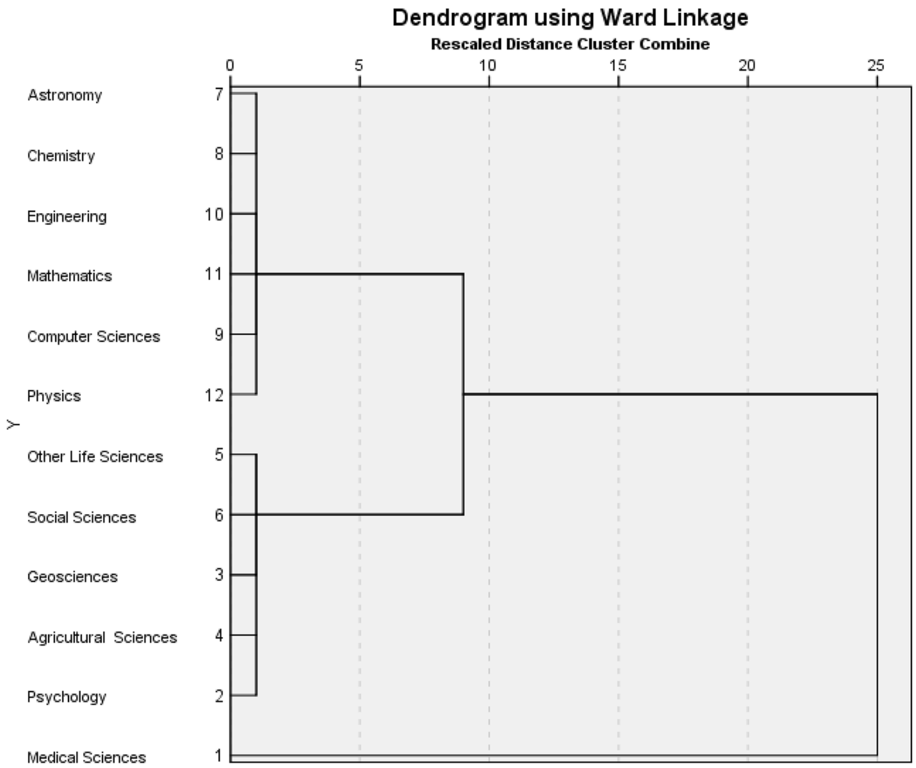

Fig. 2 Dendrogram (Squared Euclidean distance, Method Ward linkage) of scientific fields considering the similarity of the patterns of growth of international scientific collaboration

The analysis of hierarchical cluster in Fig. 2 shows three main sets of scientific fields (that include several subfields as listed in Appendix 2) with different relative growth rates of international research collaboration. In particular,

1. Medical Sciences has the highest growth rate of international research collaboration during 1997–2012;
2. Social Sciences, other Life Sciences, Geosciences, Agricultural Sciences, and Psychology have high growth rates of international research collaboration;
3. Astronomy, Chemistry, Mathematics, Computer Sciences, and Physics and Engineering have low growth rates of international research collaboration.

In order to generalize the results, as far as possible, we can categorize the scientific fields in basic and applied fields, though in social studies of science this topic is the subject of ongoing discussion due to changing frontiers of research disciplines during the evolution of science (Kitcher 2001). Frame and Carpenter (1979, pp. 483–484) proposed that predominantly *basic fields* include Astronomy (similar to Space Science), Physics, Mathematics, and Biomedical Research; whereas, *applied or clinical fields* include Biology, Agricultural Research, Psychology, Clinical Medicine, and Engineering/Technology. Many studies argue that chemistry and biology are the two disciplines encountering more debate in being classified in basic or applied fields (Frame and Carpenter 1979; Boyack et al. 2005; Small 1999). In their analysis of the global structure of the sciences, Boyack et al. (2005) showed chemistry in the same area of mathematics and physics. Simonton (2004), analyzing the Comtean hierarchy of the science, also displayed chemistry at the top of the hierarchy, close to physics. Smith et al. (2000) considered chemistry and physics with about the same rated hardness, which is characterized by a high degree of rigor. These studies suggest to locate chemistry in basic fields. Biology, as said, is another discipline in the middle ground between basic and applied sciences (Small 1999; Simonton 2004; Klavans and Boyack 2009). Frame and Carpenter (1979) placed the biology in applied or clinical fields. Studies of the map of science show that biological research fields are rather close to medicine and other applied disciplines (Boyack et al. 2005; Glänzel and Schubert 2003). Hence, based on this literature, we locate biology in predominantly applied fields. Regarding computer science, Glänzel and Schubert (2003, pp. 358–359) classify this research field within engineering (an applied research field). The map by Small (1999, p. 805) also shows that geoscience contains specialized topics—geological evolution and earthquakes—and social sciences include disciplines such as economics, sociology, law and so on, that are rather close to psychology area due to several co-citation links. This result is confirmed in the map of science by Boyack et al. (2005, p. 365).

Overall, these studies of the global structure of science, when taken together, suggest there is utility to categorizing the disciplines under study into basic and applied research categories and scholars seem to be able to so with a relatively high degree of convergent validity (Frame and Carpenter 1979; Boyack et al. 2005; Small 1999; Simonton 2004; Storer 1967; Smith et al. 2000, 17–25; Klavans and Boyack 2009; Boyack 2004; Fanelli and Glänzel 2013). In general, the findings of this paper, considering a coherent categorization of applied and basic sciences based on literature mentioned above, seem to show that:

- Predominantly applied research fields (e.g., Social Sciences, Other Life Sciences, Geosciences, Agricultural Sciences, Psychology, etc.) have high growth rates of international collaboration;
- Predominantly basic fields (e.g., Astronomy, Chemistry, Mathematics, Physics, etc.) have low growth rates of international research collaboration.

In general, different specializations within research fields exhibit different levels of activity (e.g. publication growth rate, author growth rate, etc.), and so possibly by extension, different propensities for patterns of international research collaboration. This result is confirmed by Coccia and Wang (2016), using the fraction of papers which have international institutional co-authorships for various fields of science. In particular, Coccia and Wang (2016) show that the relative changes of international scientific collaboration in predominantly basic fields (e.g. Physics and Mathematics) have declined, whereas those in predominantly applied research fields (e.g. Clinical Medicine) have risen from 1973 to 2012.[1]

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[1] This study by Coccia and Wang (2016) also shows the interesting property of convergence between basic and applied sciences during the on-going evolution of patterns of international scientific collaboration. The preliminary study of this vital finding has started in 2011 at Georgia Institute of Technology (cf., Coccia, 2012 "Evaluation of scientific collaborations of research institutions across countries to design fruitful research policy and support active knowledge trajectories", *Final Report of Research Project* (*0040055-2011*) *of the Memorandum CNR—National Research Council of Italy and National Endowment for the Humanities* (*USA*), Georgia Institute of Technology, Atlanta, USA (19th April 2012). Results of this research project were also presented at Congress AIV (University of Milan-Italy, 18th–19th April, 2013).

Hence, empirical analysis here shows a relative growth of international research collaboration across all research fields, however main differences (*variety*) appear across research fields (*see*, Figs. 1 and 2): the medical sciences and some specific applied research fields, as described above, have a disproportionate relative growth of internationally co-authored articles in comparison to domestic ones only; vice versa for predominantly basic fields.

Discussion and conclusion

This study provides a new approach for measuring and analizing the changes in the growth patterns of international research collaboration across research fields. On the basis of the results presented in this paper, we can therefore conclude with some properties of the patterns of international scientific collaboration:

1. Acceleration of the internationalization of research collaborations across all research fields.
2. Acceleration is most pronounced in applied disciplines, including particularly medical sciences and allied medical fields, and psychology. These predominantly applied fields seem to have a high level of relative growth of internationally co-authored articles, as charted by our analysis of allometric growth rates.
3. Low relative growth of international research collaboration is across more basic research fields, such as Astronomy, Chemistry, Mathematics, Physics, etc.

At this point it is natural that the reader should ask a question about these results. For instance, why some scientific fields have accelerated the growth of international research collaboration.

A possible answer to this question is that our key results give specificity to general observations about the current evolution of science, which is a system evolving toward greater international scientific collaboration but in different patterns in different research fields (cf., Coccia and Wang 2016). Perhaps the most interesting finding of this study is the unparalleled growth (over 1997–2012) of the medical sciences and some related applied disciplines in comparison to the past. We and others have suggested some of the underlying reasons for increased international collaboration and for diversity of growth according to scientific fields (cf., Luukkonen et al. 1992; Coccia and Wang 2016). It seems that external factors to science (such as easier, better and cheaper means of transportation and communications, and technological change in general) considerably affect the growth of *all* collaboration patterns (cf., Teasley and Wolinsky 2001). The possible determinants of high growth rates in specific fields may be due to the emergence of new disciplines by either a process of outgrowth from one specific discipline or through a combination of multiple scientific fields. In particular, emerging disciplines, mainly of applied or clinical fields (e.g., Biomedical Engineering, Biochemistry, Molecular Biology, etc.) seem to support patterns of international research collaboration for medical sciences (cf., Coccia et al. 2012; Coccia 2012a, b, c; 2013). Boyack et al. (2005, p. 367) claim that: "biochemistry is clearly one of the hubs of science. It is the largest discipline, both in terms of numbers of journals and number of citations". Newman (2004, p. 5204) shows that "Biological scientists tend to have significantly more co-authors than mathematicians or physicists, a result that reflects the labor intensive, predominantly experimental direction of current biology". These emerging research fields are *hybrid disciplines* with main features of both applied and basic sciences that can lead to higher scientific collaboration. Psychology has also been the focus of increased international collaboration that may be due to a fruitful interrelationship with cognitive sciences (Schunn et al. 1998, p. 108*ff*, 2004; cf., Stillings et al. 1987). This study confirms that the science system is a "living and evolving organism" (Science 1965, p. 737) with emerging fields and an increased interaction between new and traditional scientific disciplines. One of contributing factors of current patterns of international scientific collaboration may be due to a *plexus* of research fields in science: an interwoven combination of research fields and sub-research fields, which pervades the evolution of science and, especially, supports the development (production and collaboration) of emerging research fields (Sun et al. 2013; Coccia 2012a).

Alternative explanations of the high relative growth of predominantly applied fields may be also due to some theories that consider the main role of the social interaction among groups of scientists "as the driving force behind the evolution of disciplines" (Sun et al. 2013 p. 1; cf., Crane 1972a; Guimera et al. 2005; Wagner 2008). Instead, other social studies of science suggest that the interdisciplinary of some research fields induces high growth rates of international research collaboration by means of research teams with both theoretical and applied scientists from different international research institutions (cf., Wuchty et al. 2006; US National Research Council 2014). In fact, emerging research fields, such as biochemistry that now plays a vital role in the development of biological and medical sciences, are driven by scholars that converge from "multiple scientific backgrounds" of several international institutions (Battard 2012, p. 235; cf., Jeffrey 2003; Coccia and Rolfo 2007, 2013; Coccia 2005a, 2008a, 2014c; Bozeman et al. 2013; Crow and Bozeman 1998). Nanotechnology is another emerging research field with the feature of high interdisciplinary and international scientific collaboration (cf., Coccia et al. 2012; Coccia 2012d, e; Coccia and Wang 2015). These new disciplines can also support "the rise of research network" (Adams 2012; Uddin et al. 2013; Newman 2001, 2004) and "teams in production of knowledge" (Wuchty et al. 2006) for sharing competencies, instrument, resources and data (Coccia 2001, 2009a, b; Crow and Bozeman 1998). In brief, these factors are main drivers of international research collaboration of predominantly (applied) research fields.

With regards to basic research fields, such as astronomy and physics, they have an international research collaboration history due to their involving theoretical problems of universal interest, such as the discovery of gravitational waves (Scientific American 2016; cf. *also* Storer 1970; Frame and Carpenter 1979; Luukkonen et al. 1992; Crane 1972b) and, perhaps even more importance, their reliance on large-scale scientific equipment and research facilities, necessary for sharing and analyzing big scientific data (Beaver de and Rosen 1978; cf., Hara et al. 2003; Freeman et al. 2014).

Overall then, these factors just mentioned may explain the social dynamics of science that will continue to evolve with an international dimension and a deeper unity will be found among its parts (research fields).

However, we know that other things are often not equal over time and space. Especially limiting is the fact that our approach to analysis did not permit some controls and intervening variables that may have been useful in providing a deeper and richer explanation of the phenomena of interests. In short, we emphasize that our conclusions are tentative. Much work remains if we are to understand in more depth the reasons for and the implications of greater internationalization in patterns of scientific research collaboration. In particular, more fine-grained studies will be useful in future, ones that can more easily examine other complex predictors of international collaboration trends. Most of our focus is on disciplines clearly important but not sufficient for broader understanding of the dynamic patterns of international scientific collaboration in the domain in science.

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Appendix 1: Countries included in the sample

Argentina, Australia, Austria, Belgium, Brazil, Canada, Chile, China, Czech Republic, Denmark, Egypt, Finland, France, Germany, Greece, Hungary, India, Iran, Ireland, Italy, Israel, Japan, Mexico, New Zealand, Norway, Poland, Portugal, Russia, Saudi Arabia, Singapore, South Africa, South Korea, Spain, Sweden, Switzerland, Taiwan, The Netherlands, Turkey, United Kingdom, United States of America (*Source:* National Science Foundation 2014).

Appendix 2: Fields and their subfields under study

Engineering
Aerospace engineering
Chemical engineering
Civil engineering
Electrical engineering
Mechanical engineering
Metals and metallurgy
Materials engineering
Industrial engineering
Operations research and management
Biomedical engineering
Nuclear technology
General engineering
Miscellaneous engineering and technology
Astronomy
Chemistry
Analytical chemistry
Organic chemistry
Physical chemistry
Polymers

Biological sciences
General biomedical research
Miscellaneous biomedical research
Biophysics
Botany
Anatomy and morphology
Cell biology, cytology, and histology
Ecology
Entomology
Immunology
Microbiology
Nutrition and dietetics
Parasitology
Genetics and heredity
Pathology
Pharmacology
Physiology
General zoology
Miscellaneous zoology
General biology

Medical sciences (continued)
Urology
Nephrology
Allergy
Fertility
Geriatrics
Embryology
Tropical medicine
Addictive diseases
Microscopy
Other life sciences
Speech/language pathology and audiology
Nursing
Rehabilitation
Health policy and services
Psychology
Clinical psychology
Behavioral and comparative psychology
Developmental and child psychology
Experimental psychology

General chemistry	Miscellaneous biology	Human factors
Applied chemistry	Biochemistry and molecular biology	Social psychology
Inorganic and nuclear chemistry	Virology	General psychology
Physics	*Medical sciences*	Miscellaneous psychology
Acoustics	Endocrinology	Psychoanalysis
Chemical physics	Neurology and neurosurgery	*Social sciences*
Nuclear and particle physics	Dentistry	Economics
Optics	Environmental and occupational health	International relations
Solid state physics	Public health	Political science and public administration
Applied physics	Surgery	Demography
Fluids and plasmas	General and internal medicine	Sociology
General physics	Ophthalmology	Anthropology and archaeology
Miscellaneous physics	Pharmacy	Area studies
Geosciences	Veterinary medicine	Criminology
Meteorology and atmospheric sciences	Miscellaneous clinical medicine	Geography and regional sciences
Geology	Anesthesiology	Planning and urban studies
Earth and planetary sciences	Cardiovascular system	General social sciences
Oceanography and limnology	Cancer	Miscellaneous social sciences
Marine biology and hydrobiology	Gastroenterology	Science studies
Environmental sciences	Hematology	Gerontology and aging
Mathematics	Obstetrics and gynecology	Social studies of medicine
Applied mathematics	Otorhinolaryngology	
Probability and statistics	Pediatrics	
General mathematics	Psychiatry	
Miscellaneous mathematics	Radiology and nuclear medicine	
Computer sciences	Dermatology and venereal disease	
Agricultural sciences	Orthopedics	
Dairy and animal sciences	Arthritis and rheumatism	
Agricultural and food sciences	Respiratory system	

Source: National Science Foundation (2014)

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