Scientometrics (2018) 117:1265–1283
https://doi.org/10.1007/s11192-018-2902-8

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General properties of the evolution of research fields: a scientometric study of human microbiome, evolutionary robotics and astrobiology

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Received: 16 May 2018 / Published online: 14 September 2018

Abstract

How do research fields evolve? This study confronts this question here by developing an inductive analysis based on emerging research fields of human microbiome, evolutionary robotics and astrobiology (also called exobiology). Data analysis considers papers associated with subject areas of authors from starting years to 2017 per each research field under study. Findings suggest some empirical properties of the evolution of research fields: the *first property* states that the evolution of a research field is driven by few disciplines (3–5) that generate more than 80% of documents (concentration of scientific production); the *second property* states that the evolution of research fields is path-dependent of critical disciplines: they can be parent disciplines that have originated the research field or new disciplines emerged during the evolution of science; the *third property* states that the evolution of research fields can be also due to a new discipline originated from a process of specialization within applied or basic sciences and/or convergence between disciplines. Finally, the *fourth property* states that the evolution of specific research fields can be due to both applied and basic sciences. These results here can explain and generalize some characteristics of the evolution of scientific fields in the dynamics of science. Overall, then, this study begins the process of clarifying and generalizing, as far as possible, the *general properties* of the evolution of research fields to lay a foundation for the development of sophisticated theories of the evolution of science.

Keywords Research fields · Evolution of science · Dynamics of science · Convergence in science · Applied sciences · Basic sciences · Human microbiome · Evolutionary robotics · Astrobiology · Exobiology

JEL Classification A19 · C00 · I23 · L30

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Introduction

This paper has two goals. The first is to analyse the evolution of emerging research fields in applied and basic sciences. The second is to suggest empirical properties that can explain and generalize evolutionary pathways of research fields over time and space.

The role of science and scientific fields has been explored from different perspectives (Coccia and Wang 2016; Coccia and Bozeman 2016; Freedman 1960; Lee and Bozeman 2005; Merton 1968; Stephan 1996). Many studies have investigated the global structure of science to explain the differences between fields of research and categorize them in applied and basic sciences (Börner and Scharnhorst 2009; Boyack et al. 2005; Simonton 2004). Other studies endeavour to explain the role of social interactions in shaping the dynamics of science and the emergence of disciplines (Sun et al. 2013). In general, scientometric analyses of the nature and evolution of research fields are important topics for detecting characteristics to categorize research fields and explain their evolutionary pathways in science (Tijssen 2010; Van Raan 2000).

However, how research fields evolve over time, it is a scientific issue hardly known. Stimulated by this fundamental problem in the field of scientometrics and social studies of science, this paper endeavours to explain the following questions:

- How do scientific fields evolve?
- Which are general characteristics of the evolutionary pathways of scientific fields?

The literature about these questions is rather scarce but these topics are critical to science and society for understanding the evolution of scientific fields, supporting the management and organizational behaviour of public research labs, and designing a research policy directed to develop science advances and new technology (Coccia 2005, 2011, 2014, 2017; Coccia et al. 2015; Coccia and Cadario 2014; Coccia and Rolfo 2009, 2010, 2013; Kitcher 2001; Storer 1967; Stephan and Levin 1992; Sun et al. 2013). In particular, this study confronts the questions just mentioned by developing an inductive analysis, which endeavours to explain evolutionary characteristics of research fields both in applied and basic sciences,[1] such as Human Microbiome (in short Microbiome), Evolutionary Robotics and Astrobiology (also called Exobiology). Results of this study may explain and generalize, whenever possible properties of the evolution of research fields to predict their evolutionary pathways over time and space. This study can also support best practices of research policy for guiding funding for R&D towards new fields that are likeliest to evolve rapidly in society (Börner et al. 2011). In order to position this study within existing literature, next section begins by reviewing accepted theoretical frameworks about these topics in social study and philosophy of science.

Theoretical background

Numerous studies have been done over the past fifty decades about the concept of science, the mapping and evolution of science (cf., Boyack 2004; Boyack et al. 2005; Coccia and Wang 2016; Coccia and Bozeman 2016; Fanelli and Glänzel 2013; Merton 1968; Simonton 2002; Small 1999; Smith et al. 2000; Stephan 1996; Sun et al. 2013). Freedman (1960, p. 3) argues that: "Science is a form of human activity through pursuit of which mankind acquires an increasingly fuller and more accurate knowledge and understanding

[1] cf., Coccia and Wang (2016, p. 2059) for categorization of applied and basic fields of research.

of nature, past, present and future, and an increasing capacity to adapt itself to and to change its environment and to modify its own characteristics".

This study focuses on the evolution of research fields in science. A brief background of the concept of evolution is useful to clarify this study. Evolution is a stepwise and comprehensive development [it derives from Latin *evolution –onis*, der. of *evolvĕre* = act of carrying out (the papyrus)]. The dominant paradigm about the evolution of science during the 1960s was the approach of scientific paradigm shift developed by Kuhn (1962). Scientific development is based on a long-range evolution of "normal science".[2] Scientific advances in this approach include both radical changes of theory that have a significant impact on several disciplines and changes of theory whose consequences are within a specific scientific discipline in which the change has taken place (Andersen 1998, p. 3). Moreover, in this theory, scientific paradigm shift can be major in the presence of discontinuity with previous theoretical framework (e.g., the theory of relativity in physics), and minor whether it generates continuity between successive paradigms (e.g., nanoparticle-delivered chemotherapy in oncology). In general, major or minor paradigm shifts support the long-run development of science and research fields. In particular, the evolution of research fields is due to major paradigm shifts, made possible by numerous minor paradigm shifts and continuous development of normal science. Moreover, the short-term evolution of research field is due to changes within the research field, whereas the long-term evolution is possible by increasingly interaction of inter-related research fields.

A second approach about the evolution of science, during the 1970s, is developed by Lakatos (1978) with the concept of research programme. Lakatos (1978, p. 168ff) argues that: "science… can be regarded as a huge research program…. if in the process it leads to a progressive problem-shift".

Another distinct class of approaches investigates the social interactions in shaping the dynamics of science. In this context, Sun et al. (2013) argue that research fields evolve from diversification and/or merger of scientific communities within collaboration networks. Sun et al. (2013, p. 4) also claim that the socio-cognitive interactions of scientists and scientific communities play a vital role in shaping the evolution of scientific fields. One strand of this literature about the evolution of science, often referred to as the social construction of science, has investigated international collaboration between research organizations for its impetus in fostering scientific breakthroughs, technological advances, and other events that are fundamental determinants of the dynamics of science (cf., Coccia and Bozeman 2016; Latour 1987; Latour and Woolgar 1979). Coccia and Wang (2016) show, with empirical data, that the evolution of science generates convergence of international scientific collaboration between applied and basic sciences. These approaches have their roots in an older discussion about the role of international research collaboration across scientific fields and the interdisciplinary in science (cf., Storer 1970; de Beaver and Rosen 1978; Frame and Carpenter 1979; cf., De Solla Price 1986; Newman 2001; Mulkay 1975; Sun et al. 2013). Morillo et al. (2003, p. 1237) claim that research fields are increasing the interdisciplinary because of a combination of different bodies of knowledge and new communities of scholars from different disciplines to solve more and more complex problems in nature and society (cf., Coccia 2016a, b). In addition, interdisciplinary in science can generate new research fields, such as nanotechnology, biomedicine,

[2] " 'normal science' means research firmly based upon one or more past scientific achievements that some particular scientific community acknowledges for a time as supplying the foundation for its further practice'' (Kuhn 1962, p. 10, original emphasis).

etc. (Coccia 2011, 2016a, b, 2017; Gibbons et al. 1994; Guimera et al. 2005; Klein 1996; Sun et al. 2013; Wagner 2008).

Other studies have suggested that one of the factors supporting the evolution of research fields is due to new technology, such as the paradigm shift of the discovery of quasiperiodic crystal in metallurgy and materials processing science by using the technological innovation of transmission electron microscopy (cf., Coccia 2016a). In short, the evolution of research fields is a constant process driven by different scientific disciplines, new technology and socioeconomic factors that generate a stepwise development of applied and basic sciences to solve consequential problems in nature and society (cf., Coccia 2016b).

In general, scientific fields are not static entities but they change dynamically during the evolution of science (Coccia and Wang 2016; Sun et al. 2013). These changes are progressive processes because of the essential nature of scientific progress in society (Simonton 2004, p. 65). Hence, while several studies exist in social studies of science and scientometrics, characteristics and properties underlying the evolution of research fields are unknown. This paper here endeavours to analyse the temporal aspects of some research fields in applied and basic sciences to suggest general properties that are validated on the basis of empirical data. Next section presents the materials and methods of this study to analyse data, explain and generalize, as far as possible, the long-term development of research fields.

Materials and methods

Discipline is a vital concept in science: it derives from Latin *disciplina*, derivation of *discĕre* =to learn. In particular, scientific discipline is a system of organized and systematized norms, theories and principles, established and developed by specific methods of inquiry directed to solve problems and explain phenomena in nature and society. A research field is a sub-set of a discipline that investigates specific topics and/or phenomena to solve and clarify theoretical and practical problems that can generate science advances in applied and/or basic sciences.

The empirical data of this study are downloaded from Scopus (2018). In particular, this study uses the tool "document search" of Article title, Abstract, Keywords in Scopus (2018) concerning the research fields of microbiome, evolutionary robotics and astrobiology/exobiology. This study assumes that disciplines underlying research fields are the subject areas as indicated by Scopus (2018).

The steps performed for data collection are:

1. The search in Scopus (2018) of the keywords of emerging research fields: "microbiome", "evolutionary robotics" and "astrobiology/exobiology" (tool "document search").
2. For these research fields, data are from the first year indicated in Scopus to 2017 (year 2018 is not included here because data are in progress).
3. Every year in Scopus (2018) is selected and the following information are collected and analysed per each research field:
   - Number of documents over time and information about the initial year concerning these research fields to detect the origin and evolution. In particular, the assumption here is that the year in which it is appeared the document with the first use and/or study of new concepts, it indicates the origin of research field. The number of documents over time indicates the evolution of research fields.

- Subject areas are a proxy of disciplines underlying research fields, such as medicine, immunology and microbiology, etc. for human microbiome. Each subject area is associated with the university department/s of authors.

4. In a spreadsheet Excel, the above information from Scopus (2018) are systematized as follows: the first line indicates the years, for instance from 2002 to 2017 for the research field of human microbiome; the first column indicates the subject areas, such as medicine, biochemistry, genetics and molecular biology, etc. associated with documents of each research field under study. Each cell of this matrix indicates the number of affiliations associated with authorship of documents in a specific year. These affiliations, in turn, are associated with subject areas of authors. For instance, in 2002, Human Microbiome has the number 2 for subject area of medicine and 1 for immunology and microbiology, because the two authors of two documents have 3 affiliations: the author of a paper has two affiliations both in a department of microbiology and in a department of medicine; the author of the other paper has only one affiliation (in a department of medicine).
5. Data are illustrated in a graph to show the trend of publications concerning different subject areas of the research field under study (x-axis indicates years; y-axis is the total number of occurrences concerning publications in subject areas per research field). Another graph indicates the scientific weight of the occurrences of each subject area supporting the evolution of research field under study, considering applied and basic sciences as categorized by Coccia and Wang (2016, p. 2059): i.e., basic sciences include mathematics, astronomy (similar to space science), physics and chemistry; and applied research fields include biology, clinical medicine, computer science, and engineering/technology. The ratio, represented on y-axis[3] of these graphs, is given by ($i = 1,\ldots,n$; $j = 1, \ldots,m$):

$$\varphi(\text{Scientific weight of occurrences of the subject area j in the research field } i \text{ at } t) = \frac{\text{Occurrence of the subject area j in the research field } i \text{ at time } t}{\text{Total of number of occurrences in the research field i at } t} \quad (1)$$

The study here estimates the trends of research fields applying the best curve estimation model given by a model of growth with equation:

$$y = e^{a+bt} \text{ (i.e., data take off at a specific year)} \quad (2)$$

This model has dependent variable y = annually publications of the research field; explanatory variable t = time(years). Regression analyses of models also show the coefficient of determination R^2 (goodness of fit) and F-test (the ratio of the variance explained by the model to the unexplained variance). Models are estimated with the method of Ordinary Least Squares (OLS). Statistical analyses are performed by using the Software IBM SPSS® Statistics 21.

Overall, then, scientific outputs from statistical analyses can show how research fields evolve and which disciplines contribute to their evolutionary pathways to suggest empirical properties.

Results

The scientific fields under study are human microbiome (in short, microbiome), evolutionary robotics and astrobiology/exobiology.

[3] x-axis indicates the time (years).

1.1 Human microbiome

The human microbiome is a research field that investigates the accumulation and biological processes of microbes living in the human body, mainly in the gut. This emerging research field plays a vital role to explain causes of diseases, such as obesity, diabetes, gastrointestinal disorders, some cancers, etc. (cf., The American Microbiome Institute 2015). The search of the keyword "microbiome" in Scopus (2018) shows that the first article concerning this topic is in 2002 by Relman David Arnold, American microbiologist from Department of Microbiology (Stanford University, CA, United States) and US Dept. of Veterans Affairs at Palo Alto Hlth. Care Syst. in California. The article is: Relman D. A. (2002) "New technologies, human-microbe interactions, and the search for previously unrecognized pathogens", Journal of Infectious Diseases, volume 186, issue Suppl. 2, pages S254–S258. Another pioneering article in this new research field also published in 2002, is by Shanahan Fergus from Department of Medicine, University College Cork, National University of Ireland: Shanahan F. (2002) "The host-microbe interface within the gut", Bailliere's Best Practice and Research in Clinical Gastroenterology, vol. 16, issue 6, December 2002, pages 915–931. These articles suggest that the origin of this emerging research field is in the year 2002; now the scientific production in this research field is growing with geometric rates as shown in Fig. 1. The estimated relationship with regression analysis, applying a model of growth [Eq. (2): $y = e^{a+bt}$ or $\ln y = a + bt$], is described in Table 1. The $R^2 = 0.97$ is very high. Model (2) here explains more than 95% variance in the data of human microbiome.

Figure 2 shows the evolution of human microbiome based on disciplines supporting its scientific pathway. In particular, empirical analysis shows that medicine, biochemistry, genetics and molecular biology are the most important disciplines supporting the evolution of human microbiome.

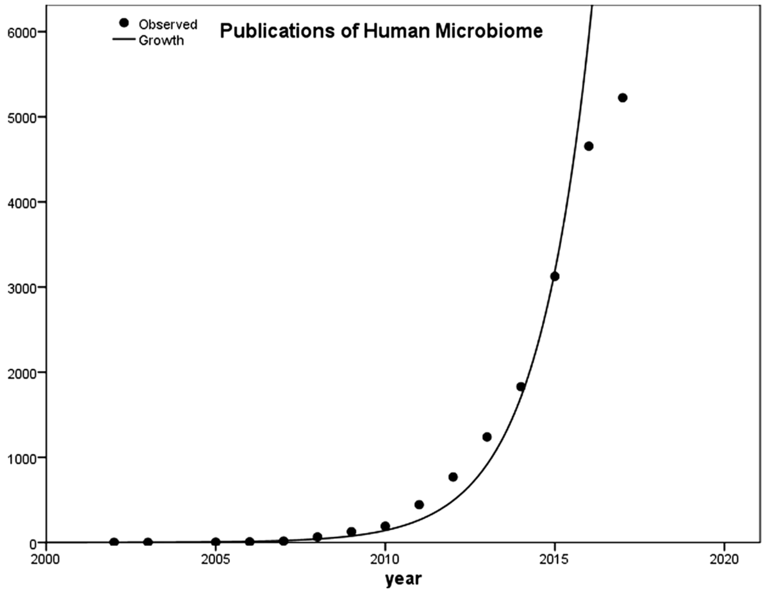

Fig. 1 Growth of the research field of human microbiome

Table 1 Estimated relationship of the evolution of research field "human microbiome"

Growth model	Constant a (St. Err.)	Coefficient b (St. Err.)	Stand. Coefficient	Adj. R^2	F (Sign.)
Dependent variable (D): Annually publications					
Explanatory variable: Time 2002–2017	− 1246.91*** (61.35)	0.62*** (0.031)	0.985	0.97	416.28 (0.001)

***Coefficient is significant at p value < 0.001

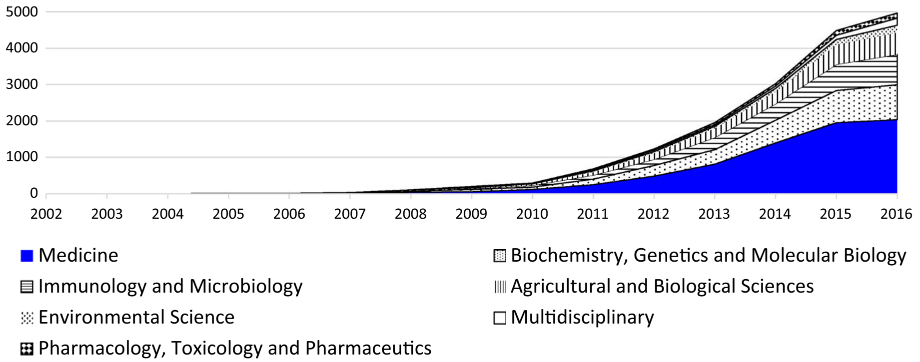

Fig. 2 Evolution of microbiome based on driving scientific disciplines. Note: y-axis is annually publications

Figure 3 shows the ratio between number of occurrences of human microbiome in each discipline in a specific year t and total number of occurrences of human microbiome in that year [Eq. (1)]. Figure 3 also shows that the research field of microbiome is originated in medicine, immunology and microbiology (parent disciplines) in 2002. These disciplines play even now a driving role in the evolution of microbiome, but other

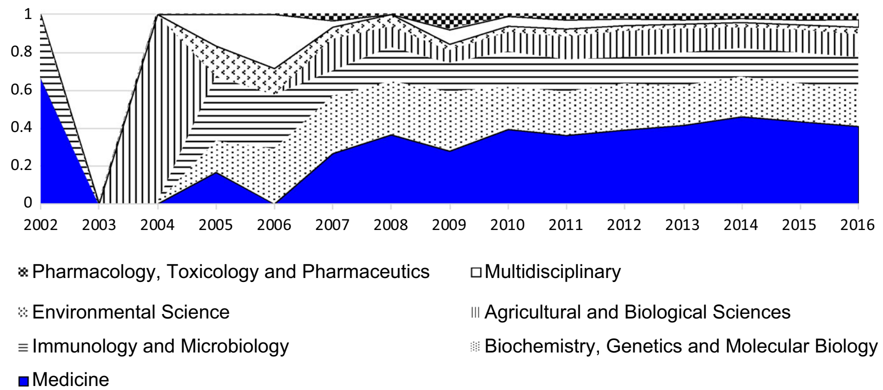

Fig. 3 Scientific weight of disciplines supporting the scientific production in human microbiome. Note: y-axis is based on Eq. (1)

disciplines are also supporting the evolutionary growth of human microbiome over time, specifically: biochemistry, genetics and molecular biology, agricultural and biological sciences. Moreover, 80% of total scientific production in the research field of microbiome is due to four disciplines: medicine; biochemistry, genetics and molecular biology; immunology and microbiology; and agricultural and biological sciences.

This statistical analysis suggests main findings for human microbiome:

- Path-dependence of the evolution of this research field from parent disciplines in which it is originated: Medicine and Immunology-Microbiology.
- Concentration of the production, supporting the evolution of this research field, is in four disciplines: medicine, biochemistry-genetics-molecular biology, immunology and microbiology, agricultural and biological sciences.
- The origin and evolution of "human microbiome" is due to disciplines of applied sciences.

1.2 Evolutionary robotics

Floreano et al. (2008) state that: "Evolutionary Robotics is a method for automatically generating artificial brains and morphologies of autonomous robots. This approach is useful both for investigating the design space of robotic applications and for testing scientific hypotheses of biological mechanisms and processes". The search of the keyword "evolutionary robotics" in Scopus (2018) shows that the first article concerning this topic is due to the American Mathematician Rudolf von Bitter Rucker when he worked at mathematical institute of the Ruprecht Karl University of Heidelberg in Germany. Rucker Rudolf in 1980 published an article that can be considered the root source of evolutionary robotics: Rucker R. (1980) "Towards robot consciousness", Speculations in Science and Technology, volume 3, issue 2, June, pages 205–217. This new research field, from 1980, has grown with accelerated rates, in particular during 1990s and 2000s (Fig. 4).

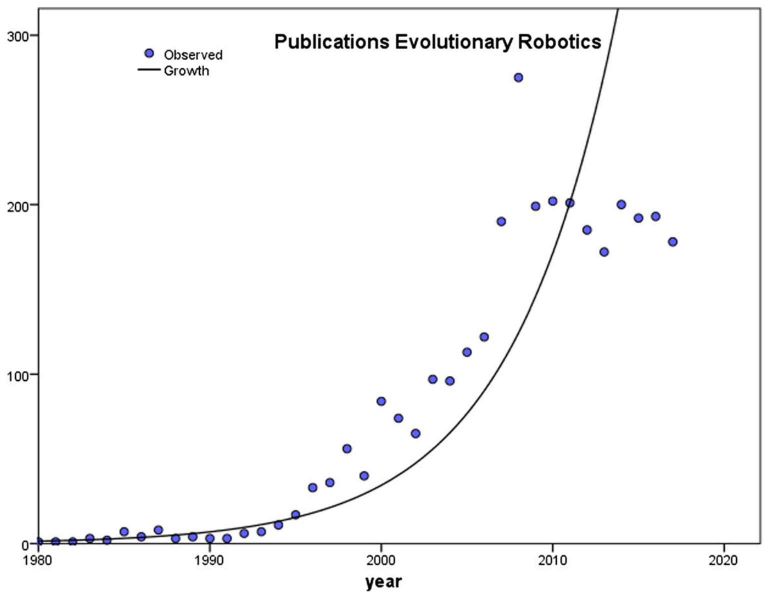

Fig. 4 Growth of the research field of evolutionary robotics

The estimated relationship of annually publications on time (years) -model of growth (2)- is in Table 2. The R^2 explains more than 90% variance in the data (Table 2).

Figure 5 shows that evolutionary robotics is driven mainly by computer science, engineering, mathematics, biochemistry, genetics and molecular biology and finally by neuroscience.

Figure 6 shows the scientific weight of disciplines supporting the evolutionary robotics over time [Eq. (1)]. In particular, evolutionary robotics is originated in 1980 within the subject area of mathematics that now has a minor contribution to the development of this research field. Subsequently, the discipline of engineering has driven the development of this research field of "evolutionary robotics", though now it is also reducing its incidence. From 1990s, the computer science is driving the evolution of this research field. In addition, 80% of total scientific production in "evolutionary robotics" is generated by three disciplines (subject areas): computer science, engineering and mathematics (Fig. 6).

The statistical analysis of "evolutionary robotics" suggests main results:

Table 2 Estimated relationship of the evolution of the research field "evolutionary robotics"

Growth model	Constant *a* (St. Err.)	Coefficient *b* (St. Err.)	Stand. Coefficient	Adj. R^2	*F* (Sign.)
Dependent variable (*D*): Annually publications					
Explanatory variable: Time 1980–2017	− 317.31*** (16.99)	0.16*** (0.009)	0.953	0.91	355.73 (0.001)

***Coefficient is significant at *p*-value < 0.001

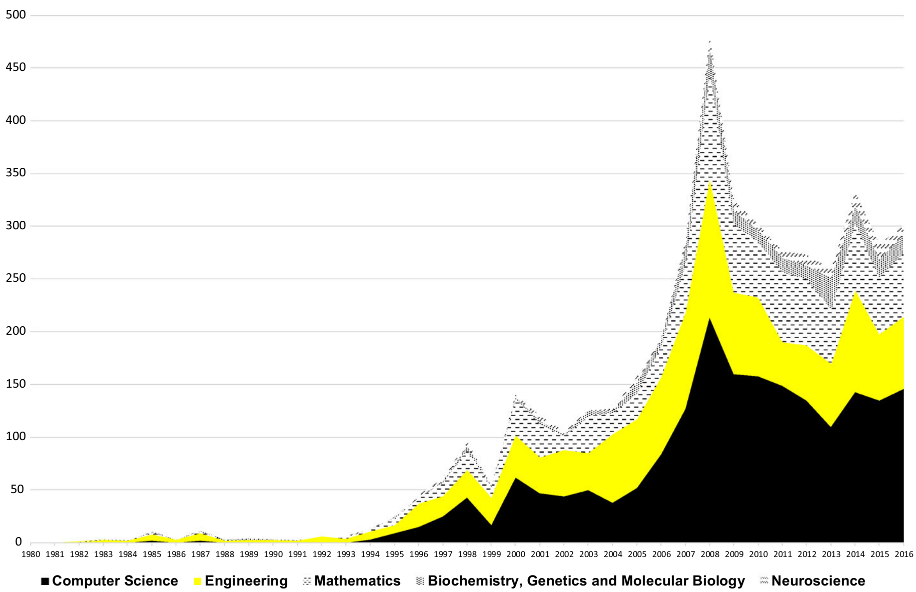

Fig. 5 Dynamics of evolutionary robotics based on driving disciplines. Note: *y*-axis is annually publications

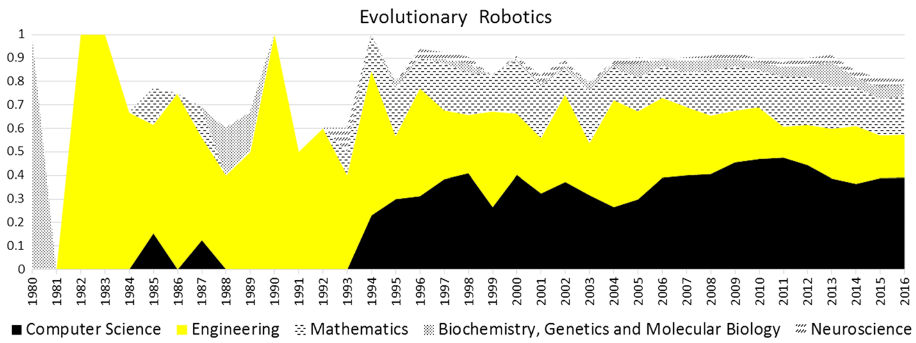

Fig. 6 Scientific weight of disciplines in the evolution of the research field of evolutionary robotics. Note: *y*-axis is based on Eq. (1)

- Decreasing role of parent disciplines that have originated the "evolutionary robotics" (i.e., mathematics and engineering) and the driving role of computer science from 1990s onwards.
- The scientific production is concentrated in three disciplines. Namely, computer science, engineering, biochemistry, genetics and molecular biology.
- The origin of this research field is in basic sciences, i.e. mathematics, but the evolution is due to applied sciences, namely engineering, computer sciences, etc.

1.3 Astrobiology/exobiology

Astrobiology is a research field that investigates: "cosmic prebiotic chemistry, planetary evolution, the search for planetary systems and habitable zones, extremophile biology and experimental simulation of extraterrestrial environments, Mars as an abode of life, life detection in our solar system and beyond, the search for extraterrestrial intelligence" (International Journal of Astrobiology 2018). The NASA claims that the interaction between knowledge acquired from space exploration and astrobiology (then called exobiology) was shown, for the first time, by Joshua Lederberg, an American molecular biologist that won in 1958 the Nobel Prize in Medicine (NASA 2018a, b, c).

The search of the keyword "astrobiology" in Scopus (2018) shows that one of the first articles concerning this topic is due to Young and Johnson (1960) from U. S. Army Ballistic Missile Agency (Huntsville, Ala., United States). Young and Johnson (1960) published a letter about "Basic Research Efforts in Astrobiology", in IRE Transactions on Military Electronics, volume MIL-4, issue 2, July 1960, pp. 284–287. In 1960, Lederberg (1960) published a pioneering paper concerning this topic: "Exobiology: Approaches to life beyond the earth", Science, volume 132, issue 3424, pp. 393–400. These articles suggest that the origin of this research field is in 1960 or thereabouts; now this research field is growing with geometric rates (Fig. 7).

The estimated relationship, applying a model of growth with equation $y = e^{a+bt}$, is in Table 3.

The model (2) explains more than 80% variance in the empirical data (Table 3). Figure 8 shows that the development of astrobiology, using annually publications, is driven mainly by earth and planetary sciences, physics and astronomy, agricultural and biological sciences, finally engineering.

Figure 9 shows the scientific weight of disciplines supporting astrobiology over time. In particular, "astrobiology" is originated in 1960 mainly in the discipline of engineering that

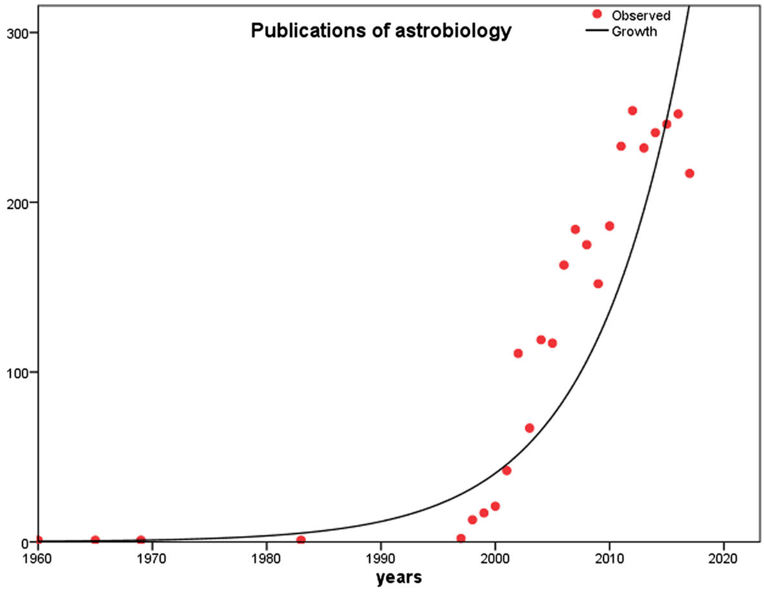

Fig. 7 Growth of the research field of astrobiology

Table 3 Estimated relationship of the evolution of research field "astrobiology"

Growth model	Constant *a* (St. Err.)	Coefficient *b* (St. Err.)	Stand. Coefficient	Adj. R^2	*F* (Sign.)
Dependent variable (*D*): Annually publications					
Explanatory variable: Time 1960–2017	− 238.81*** (21.85)	0.12*** (0.011)	0.918	0.84	123.27 (0.001)

***Coefficient is significant at p-value < 0.001

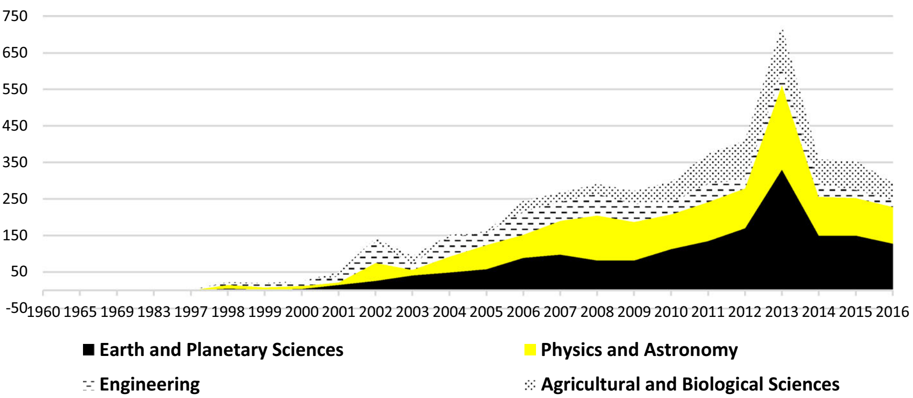

Fig. 8 Disciplines supporting the evolution of astrobiology. Note: *y*-axis is annually publications

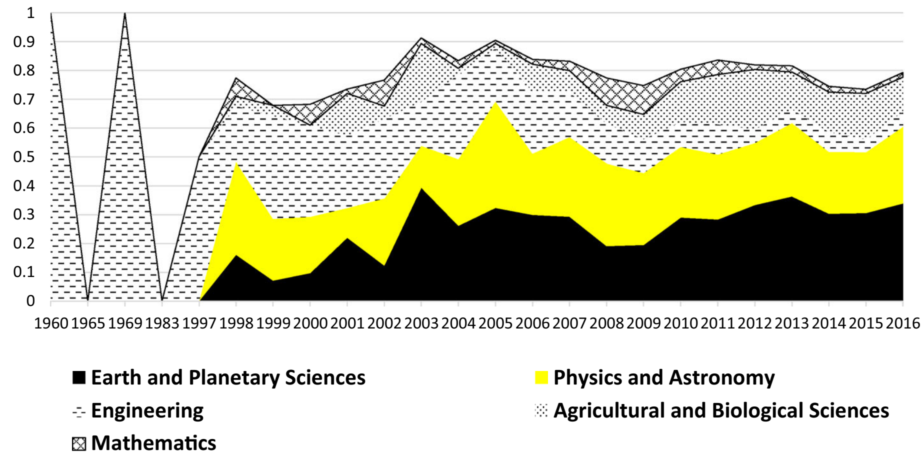

Fig. 9 Scientific weight of disciplines supporting more than 80% of scientific production in astrobiology. Note: *y*-axis is based on Eq. (1).

now has a minor role for the evolution of this research field. Subsequently, the disciplines of earth and planetary sciences, physics and astronomy, associated with agricultural and biological sciences, are driving the scientific development of "astrobiology". Moreover, 80% of total scientific production in "astrobiology" is generated by five disciplines (see, Fig. 9).

"Exobiology" is a similar research field to "astrobiology" and these concepts are often used interchangeably in science (Fig. 10).

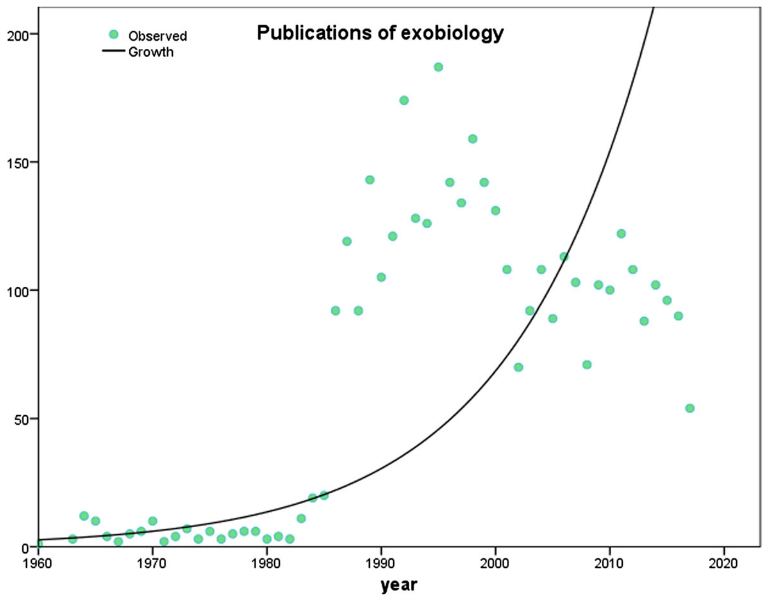

Fig. 10 Growth of the research field of exobiology

The estimated relationship of exobiology, with a model of growth (2), is in Table 4. In this case, R^2 adjusted of the model is lower in comparison with models of other research fields described above. The coefficient of determination here indicates that about 67% of the variation in publication can be attributed (linearly) to time. Alternative models about research field of "exobiology" provide the following goodness of fit to empirical data:

- Linear and cubic models have R^2 adjusted = 0.50
- Logistic model has R^2 adjusted = 0.60
- Power, S-curve, exponential and compound models have R^2 adjusted = 0.67

Hence, alternative models do not offer better goodness of fit to data, as a consequence, the growth model in Table 4 seems to provide an appropriate and reliable estimated relationship of "exobiology" similar to other research fields under study.

In addition, data of "Exobiology" also shows a lot of scatter in later years and, after 1999, there is a sustained decay of publications through 2017 (Fig. 10). This, high scatter of data in "exobiology" can be due to emergence of the twin research field of "astrobiology" and many scholars and research projects refer, currently, to "astrobiology" research field and community rather than older term of "exobiology". As said, exobiology and astrobiology are often used interchangeably in science. In fact, the NASA (2018a) has created in 1998 the NASA Astrobiology Institute (NAI) to develop the astrobiology program and provide a scientific framework for flight missions (study of the origins, evolution, distribution, and future of life in the universe). An older research project is the Exobiology and Evolutionary Biology Program established in 1959 to study the origin of life and the potential for life to exist elsewhere in the Universe (NASA 2018b).

Figure 11 shows that the evolution of "exobiology" is rather multidisciplinary. The most important disciplines for the evolution of this research field are earth and planetary sciences, agricultural and biological sciences, whereas physics and astronomy, biochemistry, genetics and molecular biology are decreasing their role over time. Medicine is also supporting the evolution of "exobiology", though at lesser extent than other disciplines. Moreover, more than 80% of scientific production in exobiology is by scholars operating in six disciplines.

The analysis of "astrobiology" suggests main findings:

- Decreasing role of parent disciplines that have originated the "astrobiology" (e.g., engineering), combined with the growing role—from 1990s—of earth and planetary sciences, agricultural and biological sciences; a steady-state contribution to the evolution of this research field is due to physics and astronomy.
- The production of astrobiology has high concentration in five disciplines (> 80% of documents) given by: earth and planetary sciences, physics and astronomy, agricultural

Table 4 Estimated relationship of the evolution of the research field "exobiology"

Growth model	Constant *a* (St. Err.)	Coefficient b (St. Err.)	Stand. Coefficient	Adj. R^2	*F* (Sign.)
Dependent variable (*D*): Annually publications					
Explanatory variable: Time 1960–2017	−157.86*** (15.31)	0.081*** (0.008)	0.82	0.67	110.90 (0.001)

***Coefficient is significant at p-value < 0.001

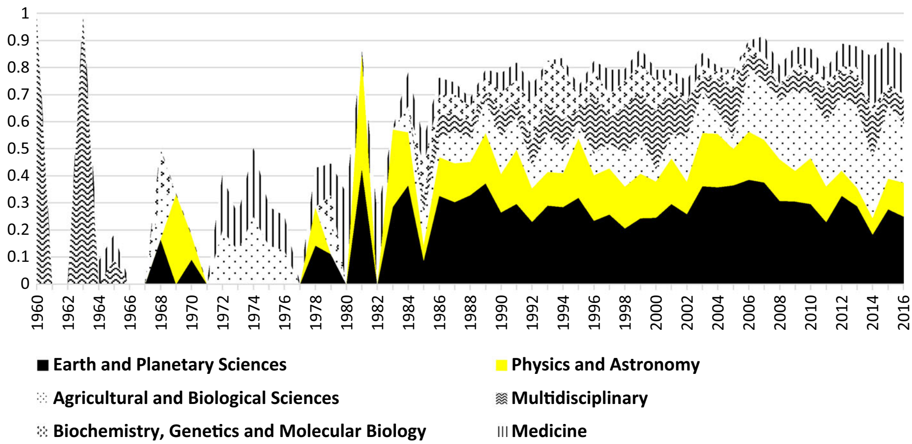

Fig. 11 Scientific weight of disciplines supporting more than 80% of production in exobiology. Note: *y*-axis is based on Eq. (1)

and biological sciences, multidisciplinary and biochemistry-genetics-molecular biology.

– The origin of “astrobiology” is in applied sciences (engineering) but the evolution is due to both applied and basic sciences, such as physics and astronomy, agricultural and biological sciences.

Exobiology has a similar evolutionary pathway. It is also driven by earth and planetary sciences, agricultural and biological sciences, and medicine. In addition, the research field of “exobiology” seems to be more interdisciplinary than astrobiology, because 80% of the production is due to six disciplines (cf., Figure 11).

General properties of the evolution of research fields

The inductive analysis here, based on three emerging research field from applied and basic sciences, suggests some empirical properties of the evolution of scientific fields.

1. *The first property* states that the evolution of a research field is driven by few disciplines (3–5) that generate more than 80% of documents (concentration of scientific production).
2. *The second property* states that the evolution of research fields is path-dependent of critical disciplines (they can be parent disciplines that have originated a research field or new disciplines originated during the evolution of applied and basic sciences).
3. *The third property* states that evolutionary pathways of a research field can be driven by a new discipline originated from a process of specialization within applied or basic sciences and/or convergence between disciplines.
4. *The fourth property* states that the evolution of research fields is due to both basic and applied sciences.

The first property indicates that the production of research fields is generally concentrated in 3–5 disciplines (considering the affiliations of authors) that support evolutionary pathways over time. In fact, Levin and Stephan (1991) argue that scientific productivity is asymmetrically distributed throughout the population of researchers (cf., Allison and

Stewart 1974; David 1994; Fox 1983). A study by Ramsden (1994) shows that, over a 5-year period, 14% of the total number of researchers produced 50% of publications, while 40% of researchers produced 80% of publications. In short, the production of scientific research has extreme inequality because high productivity of some researchers generates cumulative learning processes over time, the so-called Matthew effect in science (see, Merton 1957, 1968). This effect leads researchers/research labs/universities that accomplish prominent results at the beginning of their history to an initial advantage that increases their reputation and chances of obtaining further financial support as well as of accomplishing further discoveries over time (cf., Latour and Woolgar 1979; Latour 1987; Merton 1968).

Empirical results suggest a second property that critical disciplines can be the driving force of research fields providing scientific guideposts that lay out certain definite paths of development. Small (1999, p. 812) argues that: "the location of a field can occasionally defy its disciplinary origins." Normally, the evolution of scientific field is due to the creation of a research programme—sensu Lakatos (1978)—that guides the subsequent scientific development of research field over time.

The third property suggests that the evolution of research fields can also be due to new disciplines originated either from specialization within applied or basic sciences or through the combination of multiple disciplines (cf., Coccia and Wang 2016; Jamali and Nicholas 2010; Jeffrey 2003; Riesch 2014; van Raan 2000). In this context, Sun et al. (2013) state that social interaction among groups of scientists is: "the driving force behind the evolution of disciplines" (cf., Wuchty et al. 2007). Moreover, in the evolution of science and scientific fields, Small (1999, p. 812) argues that: "crossover fields are frequently encountered." Hence, interdisciplinarity in science can generate new disciplines that support the development of different research fields (cf., Tijssen 2010).

Finally, the fourth property states that the evolution of research fields is due to both basic and applied sciences because the dynamics of science is generating more and more a convergence between applied and basic fields of research as showed by Coccia and Wang (2016).

Discussion and concluding observations

Science is a complex and stratified process that branches in different disciplines and research fields within and between basic and applied sciences (Coccia and Wang 2016). The evolution of science and research fields is the result of a cumulative change due to exploration and solution of new and consequential problems in nature and society (cf., 2016a, b; Scharnhorst et al. 2012; Popper 1959). In general, the evolution of scientific fields can be originated from: convergence between applied and basic sciences (Coccia and Wang 2016), scientific paradigm shifts (Kuhn 1962), new research programmes (Lakatos 1978), branching of disciplines due to scientific breakthroughs, new technologies, fractionalization and specialization of general disciplines, etc. (Crane 1972; De Solla Price 1986; Dogan and Pahre1990; Mulkay 1975; van Raan 2000). The evolution of research fields is a part of the natural process of the dynamics of science guided by curiosity of scholars (a basic element of human cognition) towards the unknown, associated with other socioeconomic factors, in a context of social interactions between scientists and research institutions (cf., Adams 2012, 2013; Coccia and Wang 2016; Gibbons et al. 1994; Newman 2001, 2004; Pan et al. 2012). Sun et al. (2013, p. 3) show: "the correspondence between the social dynamics of scholar communities and the evolution of scientific disciplines".

However, literature in social studies of science does not explain general characteristics of the evolution of scientific fields over time. The results of the analysis here suggest some empirical properties for the evolution of research fields. In particular,

1. The evolution of a research field is due to few disciplines that generate more than 80% of scientific production.
2. Path-dependence of the evolution of research fields from parent disciplines in which they are originated (disciplinary origins) and/or new disciplines emerged during the dynamics of science.
3. The evolutionary pathways of research fields can be characterized by decreasing role of parent disciplines that have originated them, balanced by the increasing role of new disciplines emerged from specialization and/or convergence within/between applied and basic sciences.

These findings support empirical properties described above that can explain and generalize, whenever possible the long-term development of scientific fields.

To conclude, it would be elusive to limit the evolution of scientific fields to endogenous factors in science. The evolution of research fields is also due to manifold factors represented by social context of nations, economic growth, military and political tensions between nations to prove scientific and technological superiority, new challenges between superpowers for sustaining global leadership (such as, space exploration in 1950s–1960s; cf., Coccia 2016a, b; Small 1905, p. 682). As a matter of fact, the evolution of scientific fields is due to expanding human life-interests whose increasing realization constitutes social progress that characterizes the human nature for millennia (Woods 1907, pp. 813–815).

Overall, then, this study suggests general properties, based on empirical data, of the evolution of scientific fields that may predict their long-run behaviour in society. Moreover, these findings can support best practices of research policy for guiding funding for R&D towards new fields that are likeliest to evolve rapidly for maximizing their benefits in society.

However, these conclusions are of course tentative because we know that other things are not equal over time and space. In brief, the inductive study here cannot be enough to explain the comprehensive characteristics of the evolution of research fields and of science. One of the main problems is the difficulty of formally defining the domain of scientific fields that can change their scientific borders during the evolution of science and technology. Therefore, the identification of general patterns of science and scientific fields—at the intersection of economic, social, psychological, anthropological, philosophical, and biological factors—is a non-trivial exercise. There is need for much more detailed research to find *universals* for explaining and predicting the evolution of science and scientific fields that is more and more important for guiding the human progress in future society.

Acknowledgements The research in this paper was conducted while the author was a visiting scholar of the Center for Social Dynamics and Complexity at the Arizona State University funded by CNR - National Research Council of Italy and The National Endowment for the Humanities (Research Grant No. 0003005-2016). I thank the fruitful suggestions and comments by Ken Aiello, Sara I. Walker and seminar participants at the Beyond-Center for Fundamental Concepts in Science (Arizona State University in Tempe, USA). Older versions of this paper circulated as working papers. The author declares that he has no relevant or material financial interests that relate to the research discussed in this paper. Usual disclaimer applies.

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