Capturing the growth dynamics of science: a publication-based analysis

Sujit Bhattacharya and Shilpa*

This article attempts to identify the dynamics of knowledge production. Conceptual framework is based on research publications taken as 'proxy' indicator of research process and outcome. Indicators are constructed from research publications to capture the dynamics of research. The rationality of this approach is discussed. The study also shows that publications are increasing exponentially underscoring the intensive research undertaken globally. Determinants of publication growth have changed significantly in comparison to earlier periods. The study argues that the above determinants are indicators of changing global research structure and dynamics, and should be considered in national research and innovation policy making.

Keywords: Emerging areas, global research landscape, publication trend, scientific research.

'ONE of the obvious features of science in recent years has been its rate of growth.' This was the opening sentence of the book *Communication in Science* by Meadows in 1974 (ref. 1). This book was further exposition of Price striking claims of exponential growth of science[2,3], which he followed up with other influential works[4,5]. The scholarly research in science policy during this period highlighted how growth has been an inherent feature of science since its modern inception in the 17th century. It also underscored that scientific growth along with increase in manpower and finance, led to exponential growth of publications. Publication-based analysis (which later came to be known as bibliometrics) provided the empirically testable generalizations of growth of science and also helped delineate to some extent the structure of science[6]. It also showed that apparently meaningless counting of papers reveals a more structured picture of science than one would expect, challenging the orthodox epistemologist futility of this exercise[7].

In the contemporary period the growth of science (particularly as indicated by publication growth) is continual of the earlier findings, i.e. following an exponential pattern. However, factors that influenced scientific growth in the 1950s are different from those at present (see, for example, Edge[8]). The success of 'mission-oriented science' to develop weapon systems in the 1940s provided the first impetuous for large funding in science. This led to the articulation of science policy for promoting scientific research with liberal funding support in the 1950s and 1960s. Scientific achievements began to be linked with the prestige of a country. A particular demonstration of scientific capability and prestige was the successful research translation in space exploration[9]. Developing countries also started investing in science as they felt that they could address socio-economic challenges through scientific research and its exploitation. Publishing in peer-reviewed journals became one important reflection of scientific capability and leadership in science.

In the last two decades, major changes have occurred in science and how it is conducted[10,11]. Apart from the government, private entities have emerged as an important stakeholder in the promotion of scientific activity. A visible change is observed in the support system of science with funding getting increasingly directed towards research that can be commercially exploited. Emerging economies are increasing outlay for science, involving more people in research, developing world-class institutions and actively participating in international collaboration[12,13]. Collaborative arrangements to develop common framework and support system, joint development and access to large facilities/infrastructure are becoming an essential feature of global science[14,15]. Institutional arrangements are promoted to tackle complex research problems. However, a substantial portion of international collaboration is still bottom-up, not mediated by institution but happening primarily due to informal contacts[16].

Price's observation of exponential growth of research publications and his analytical introspection of its consequences in the 1960s had a major influence in science policy discourse at that time, providing a rational and objective assessment of science funding[8]. It also led to the foundation of conceptual framework to study

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structure and dynamics of science through publication-based analysis.

One characteristic feature which recent studies have shown is the fast growth of research publications in the contemporary period, primarily from 1990s onwards. Figure 1 highlights the transition of global publication pattern from steady growth to exponential growth since 2003 onwards[17].

The important question that drives this article is: what are the factors contributing to publication growth?

Objective

As mentioned earlier, this article identifies the determinants that are influencing scientific growth in the contemporary period. This is done using research publications as 'proxy' indicator of scientific research. The policy implications are discussed here.

Methodology

Publications in established and emerging areas were extracted to identify determinants of scientific growth. The study covers publications indexed in the Science Citation Index-Expanded (SCI-E) for the period 2000–2012. The publication records for 1990s onwards were captured in some instances to draw attention to the period from which the growth showed visible upward trend. Records were extracted for discipline-wise delineation through 156 research areas defined in the *Web of Science* (*WoS*) database. Research area categorization was applied for subject-wise delineation. The *WoS* further provides category-wise distinction for capturing research activity at more granular level. Presently, 251 categories are defined in the *WoS*. Using this category delineation the publication records in the following areas were extracted – polymer science, nanoscience and nanotechnology (NST), biotechnology, genetics, environmental engineering and manufacturing.

Further strategies were used for extracting records in key research areas/topics where the *WoS* delineation was not available. The search strategy defined by Arora *et al.*[18] was applied for extracting nanotechnology publications. The search strategies of Terekhov[19], Marx and Barth[20], Lv *et al.*[21] and Hu and Rousseau[22] were used for extracting records in fullerene, carbon nanotube, graphene and synthetic biology respectively. The Medical Subject Heading (MeSH) terms were used for extracting publication records in proteomics and genomics. Publications in stem cells and embryonic and pluripotent stem cells were extracted using query developed in a study by Elsevier[23].

Results

The determinants that were identified in this study from publication analysis are highlighted below.

Increasing assertion by emerging economies

In spite of substantial increase in publication activity in OECD countries, the significant growth in global publications is due to developing countries. China's growth is remarkable and it is now the second most prolific publishing country in the world (global share of papers from China increased from 3.2% to 14.5% during the period 2001–2012). This to an extent masks the publication growth of other emerging economies whose growth rates have also been high. Global share of papers from India increased from 1.7% in 2001 (global rank 14th) to 3.3% in 2012 (global rank 10th).

In newly emerging areas like NST, the change in global landscape is more clearly visible (Figure 2).

This pattern is also observed in popular areas of research within NST, such as graphene and carbon nanotube (CNT). For example, in 2012, China was leading in graphene research globally. South Korea and India were ranked third and seventh respectively.

Emergence of new research areas

Price[3] has shown that publication trends are similar to a logistic curve. New logistics are born due to the emergence of new fields/sub-fields from an earlier logistic curve. The shape of the global publication distribution from 1990s can be similarly discerned. Emerging areas like NST and synthetic biology play an influential role in changing the shape of the distribution from linear to exponential. However, even within fast-growing subfields, differential growth rates are observed. A good example of this is growth of research publications in NST and carbon nano-family: CNT, graphene and fullerene (Figure 3).

What is the plausible causality behind differential publication trends in the nano-carbon family? Publication trend being an indicator of research activity, it thus necessitates examining the research ecosystem of the carbon nano-family. Fullerene was discovered in mid-1980s, after which its publication trend has shown exponential growth. The discovery of fullerene in 1985 by Curl, Kroto and Smalley, the Nobel Prize awarded to them in mid-1990 and promising applications that were expected to emerge from fullerene research resulted in increasing funding in this area. Publication growth was one of the outcomes of this. In spite of significant investment in fullerene research, it did not lead to the expected promising applications and consequently, funding in this area decreased significantly. This effect can also be seen in the decrease in the number of research publications in fullerene from late 1990s onwards[24]. However, the work of Iijima[25] on CNT promising new possibilities through NST has regenerated unprecedented interest in this field. He was awarded the inaugural Kavli Prize for NST in 2008, the highest prize in NST research.

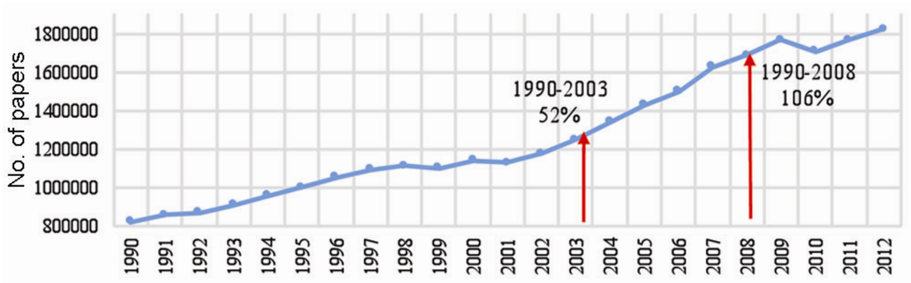

Figure 1. Publication trend of global research output in SCI-E (1990–2012). Source: SCI-E.

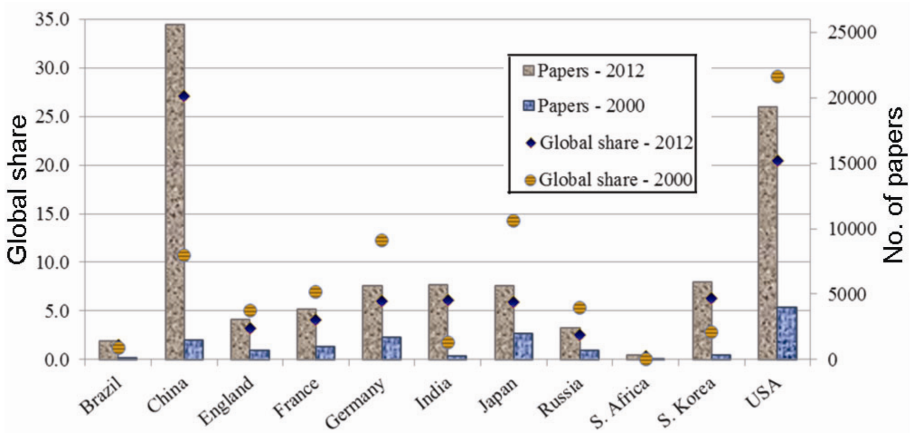

Figure 2. Nanotechnology publications and global share of some advanced OECD and emerging countries. Source: SCI-E; NST search string based on Arora *et al.*[18].

The discovery of grapheme by Geim and Novoselov in 2004, the Nobel prize awarded to them in 2010 and the simple technique for making graphene that they demonstrated can be cited as possible reasons for publication growth in this area. The curve would take a logistic shape in future because of the possibility of graphene research getting more applied, as already observed in graphene applications in high-speed electronics and flexible circuitry[26]. Fullerene, CNT and graphene are different forms of nanostructures, and changing the form from fullerene to CNT and graphene has shown the possibility of more promising applications which also led to liberal funding therein. Thus, it can be postulated that migration of the same research teams from fullerene to CNT/graphene research may have occurred due to the above reasons.

Other emerging areas are also exhibiting similar trends. Increase in publications is an indicator of research interest in these new and promising areas. A good example of this is publication growth observed in genomics, proteomics, stem cells and synthetic biology. During 1990–2012, publication increased 28 times in genomics, 9 times in synthetic biology and 58 times in stem cells. Proteomics came into existence in late 1990s, and showed 15 times increase in publication from 2000 to 2012. Research is actively undertaken in two types of stem cells, namely embryonic and pluripotent. The increase in the number of papers from 1990 to 2012 is almost 40 times in case of embryonic stem cells and 67 times in case of pluripotent stem cells.

Different social, political and cultural factors also have major influence on research[27]. A case in point is embryonic stem cell research which due to ethical and moral debate in USA was not approved by the regulatory authorities. However, pluripotent stem cells do not have similar moral and ethical concerns. As expected, pluripotent stem cell research is dominated by USA accounting for more than 40% of global papers in the area, unlike embryonic stem cell research which is more uniformly distributed globally.

New journals are coming up to address the demands of the research community in a new emerging field. Correlation is expected to be high between growth of journals and research papers as more opportunity is available for publication. A high correlation of 0.98 between these two variables is observed in NST, supporting this conjecture (Figure 4).

Increasing interdisciplinarity in established research fields

Publication growth has occurred due to substantial growth in established research and technological fields. Emergence of new research areas from parent disciplines has been a key determinant of growth. Attributes of these

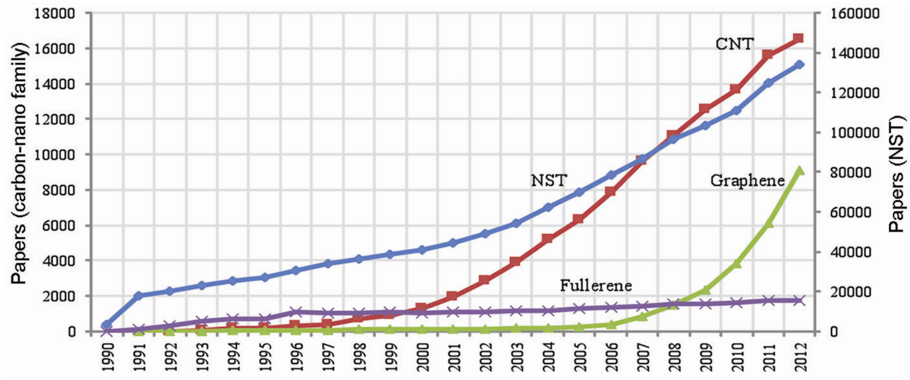

Figure 3. Publication trend in nanotechnology and carbon nano-family. Source: SCI-E; NST search string based on Arora *et al.*[18].

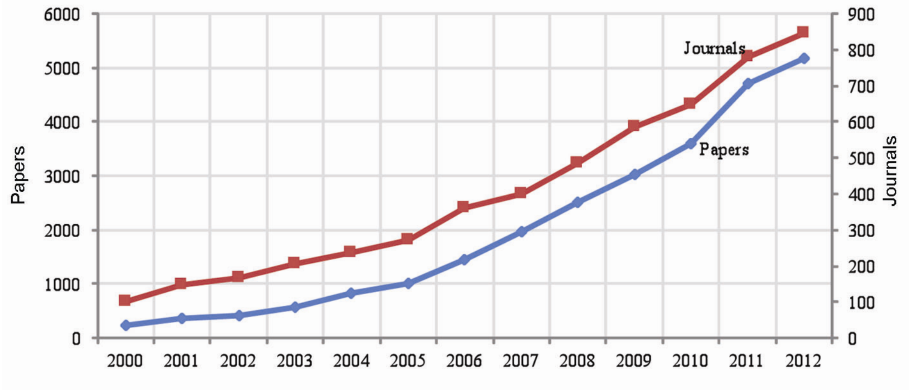

Figure 4. Nanotechnology: global publication and journal trend. Source: SCI-E; NST search string based on Arora *et al.*[18].

new areas are their interdisciplinary nature and strong interface with technology. A case in point is the research trend observed in chemistry (Figure 5).

Overall growth in chemistry doubled in absolute terms from 1990 to 2012. Two new emerging areas, namely NST and polymer sciences contributed only 0.1% and 0.5% papers respectively, in 1990 to chemistry (see note 1). In 2012, however, contribution of NST and polymer sciences to chemistry publications increased by 8% and 9.3% respectively.

Increasing research influence of these two areas of chemistry over the period can be seen as a reflection of the change in overall research activity in the two fields. In 1990s, NST and polymer sciences were in their early phase of growth. Significant increase in publications, 141 times for NST and 41 times for polymer sciences during 1990–2012 can be linked to their getting established; formation of interdisciplinary research teams being one of the outcomes of this process. This change also influenced research in parent disciplines. This can be seen, for example, in the increasing contribution of these two research areas to chemistry. On the other hand, parent disciplines are also helping in populating the newly emerging areas. For example, colloidal particle size when it reaches nanoscale is indexed under chemistry and NST subject category.

Similar trends are visible in physics, biology and engineering. Major transformation in biology is seen with the advent of biotechnology. Within biotechnology itself, one observes differential growth rates. Research activity within genetics, a dominant area of research in biotechnology, is now happening in new sub-fields within this field, namely genomics, proteomics, synthetic biology and stem cells. Publications from 1990 to 2012 almost doubled in biology, whereas for biotechnology the increase was almost four times. The publication growth in genomics, proteomics, stem cells and synthetic biology is exponential. These new areas promise major transformation of the parent science, i.e. genetics and when seen in terms of the overall field, i.e. biology, indicate radical change in this field. Significant publication growth as observed in the new sub-disciplines signals intensity of research and expansion of the research community. The publication intensity in these emerging research areas has been highlighted earlier in the article. The doubling time calculated from 1990 to 2012 highlights this further (see

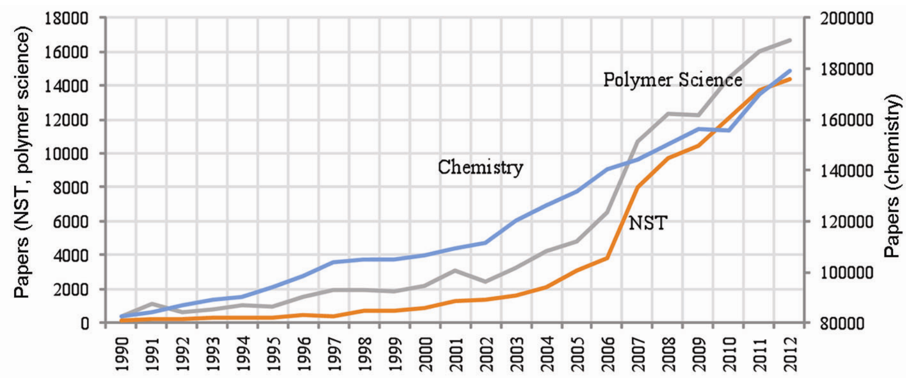

Figure 5. Publication trend in chemistry and areas of high growth within the field. Source: SCI-E; NST based on *WoS* subject-wise delineation.

Table 1. Internationally collaborative papers of some advanced OECD and emerging economies

	1990	2012
Country*	ICP (% of TP)	ICP (% of TP)
England	38,280 (41)	56,392 (50)
France	29,941 (42)	42,348 (48)
Germany	41,328 (40)	58,197 (46)
Italy	20,136 (33)	31,171 (40)
Russia	9,505 (33)	9,969 (30)
USA	96,663 (22)	142,266 (28)
Brazil	6,461 (26)	11,755 (26)
South Korea	8,081 (21)	14,866 (24)
Japan	20,783 (19)	24,588(23)
India	6,236 (18)	11,696 (18)
China	19,699 (16)	47,163 (17)

Source: SCI-E; TP: Total papers; ICP: International collaborative papers. *Countries ranked in terms of internationally collaborative papers in 2012.

note 2). The doubling time for biology is 25 years. On the other hand, doubling time for genetics, biotechnology, genomics, proteomics, stem cells and synthetic biology is 16, 5, 0.5, 1, 1 and 2 years respectively.

Physics has shown overall growth of 88% from 1990 (86,524 papers) to 2012 (162,702 papers). During this period, papers in newly emerging areas which strongly connect to this field have shown rapid growth. This is particularly observed in NST, wherein papers indexed under physics increased from 0.6% to 8% during the period.

Publications in engineering increased from 99,163 papers in 1990 to 308,261 papers in 2012, an overall increase of 61%. During this period, two areas, namely enviornmental engineering and manufacturing (active areas being automotive control systems) showed significant growth with increase in share from 2.4% to 7%, and 1% to 6.4% respectively. However, engineering in particular can only be partially reflected through research publications as a large domain of activity is in process and product development, wherein knowledge is largely of tacit nature. The codified knowledge is more visible through patents than publications, as engineering research is more connected to the downstream end of the innovation value chain.

Increasing international collaboration

The scientific world is becoming increasingly interconnected, with international collaborations on the rise. As Wagner[16] puts it, new, invisible colleges of science are continuously developing and new global networks which form an open system of learning are emerging through cooperation and various forms of collaborations. Significant rise in joint publications involving researchers from different countries provides a strong assertion of the role of international collaboration in doing science. Different research studies have shown that international collaboration depends on country 'size' (in terms of R&D investment and manpower involved in R&D). However, it is still debatable whether larger countries contribute more to international collaboration or otherwise. Schubert and Braun[28] have shown by analysing publication trends during the period 1981–1985 that the share of large countries in international collaboration is lower than that of medium-sized or even small countries. However, this trend is changing as observed from Adam's[15] examination of research publications from 1981 to 2011. This study also shows that in spite of USA's share of international publication increasing significantly, it remains less internationally collaborative than Western Europe. Further in emerging economies, the domestic share of output is a major component of its total output.

Table 1 highlights international collaborative papers of some advanced and emerging economies.

It shows how some big countries have large proportion of their papers coming from international collaborations. The findings support those of Adam[15]. Further, it is observed that Asian countries have lesser number of international collaborative papers compared to domestic papers. However, it is becoming apparent that international collaboration is an important factor in increasing global publication output. This supports the claim that global research activity is increasingly being shaped by international collaboration.

Discussion and conclusion

This article examines the causality behind exponential growth of publications in the contemporary period and argues that publication is an important indicator of scientific activity as it is an output of scientific research and its process. Thus it posits that determinants influencing publication growth reflect the structure and dynamics of the scientific landscape. The study identifies the following plausible reasons behind publication growth: increasing assertion by emerging economies, emergence of new research areas, increasing interdisciplinarity of established research fields, and increasing international collaboration.

The present study largely corroborates the findings of other studies regarding significant increase in internationally collaborative papers[14,15,29]. However, the results point to the bias that exists in collaborative research. Some large OECD and emerging economies have approximately one half of their papers coming from international collaborations, whereas for others it varies from 20% to 30% of their overall papers. However, the trend is towards increasing international collaboration in all countries. In absolute terms, we observe large volume of papers coming from international collaboration, which corresponds to about one-third of global papers. Thus publication productivity has strong correspondence with growth of international collaborative papers.

Increasing assertion by emerging and newly industrialized countries has led to more uniform distribution of research globally. The key player is China, emerging as the second most productive publishing country. China's publication growth has been dramatic with a doubling time of six months (from 1990 to 2012). India and South Korea also have a major influence in changing the global landscape. This trend is seen in emerging science-based technology areas of strategic economic and social significance such as nanotechnology.

A striking observation is that contemporary publication trend mirrors to a large extent those in the earlier periods. The observation of Meadows[1] that 'Just as the total science growth curve represents the addition of individual, often differing, curves for each branch of science, so the curves for the latter are built up from the growth curves of their various sub-fields. Typically, no sub-field shows the same rate of growth as the total field; rather each has its own life-cycle of birth, growth and decay' holds true at present too. We have observed that within chemistry, there are sub-fields that are highly interdisciplinary and show exponential growth trends with differential patterns. We have also seen this to be true for physics, biology and engineering. We further observe that even within sub-fields, areas exhibit differential growth trends. Differing growth rates are also observed in parent disciplines, sub-fields and within a sub-field, e.g. fullerene, CNT and graphene in nanotechnology. In general, our results are in agreement with the further observation made by Meadows '… so long as we concentrate on the gross outline rather than details, the increase in volume of science since the seventeenth century does have the rough appearance of an exponential function'.

The present study has limitations as it attempts to draw dynamics of the global research landscape through quantitative analysis of research publications. This to a large extent excludes tacit and many other forms of codified knowledge that construct the scientific ecosystem. The study also relies on the SCI-E database which has been criticised for bias in source selection and language barrier, and limited coverage of conference proceeding[30]. Nevertheless, SCI-E is the preferred bibliographic database of the research and policy community particularly due to rigorous process of journal selection for indexing. Further research can extend this to SCOPUS and other subject-indexed databases. At the granular level, it would be important to identify the role of academia–industry linkages, among others, in shaping publication distribution.

In spite of limitations, we argue that this study provides insight into the changing dynamics of publication growth. Based on the conceptual framework, that publication mirrors the global scientific research landscape, we posit that the factors that influence publication growth are reflection of the changing structure and dynamics of global research activity. Based on our findings, we argue for revisiting the science policy framework to see whether the policy actions of different countries incorporate strengthening interdisciplinary research and international collaboration. These two determinants have a major influence in shaping research activity globally and thus need to be promoted by a country if it wants to remain competitive or aspire to be a relevant player in global research. This study also complements the ongoing studies on understanding the global landscape of science.

Notes

1. The SCI-E database may categorize one paper in more than one research area. Papers getting indexed under multiple fields/sub-fields are particularly observed in emerging areas due their characteristic attribute of being interdisciplinary. However, the database takes care of this double counting when the total publication count of a country or global papers is made.
2. The doubling time was calculated based on Rule of 70; doubling time = (70/annual growth rate).

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