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Technological Forecasting & Social Change 74 (2007) 1334–1356

Technological Forecasting and Social Change

Opening the box: Comparing EU and US scientific output by scientific field

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Received 11 September 2006; received in revised form 24 February 2007; accepted 26 February 2007

Abstract

Recent reports suggest that, during the 1990s, the EU15 overcame the US in scientific output. This paper provides a comprehensive comparative analysis of the evolution of the EU15 and US scientific output and impact throughout the 1990s, looking at publications and impact trends by scientific field. Results show that changes in scientific production for the two blocks are driven by particular scientific fields which grew or declined at a fast rate during the decade. Throughout this period, the EU15 had eight fields of science, corresponding to a 13% of the total papers published, growing at a rate faster than 10% in relation to world average, while the US had only four fast growing fields, representing 6% of its total output. The situation was exactly reversed for the decline, with the US having more than doubled the number of scientific fields when compared to the EU15 declining at a rate faster than 10%. Despite this recent trend, the US maintains a distant leadership in impact across all scientific fields. A detailed analysis of the EU15 countries shows some convergence in terms of outputs and impact, but considerable differences among countries remain. These reflect the evolution, not only of their science, technology and higher education systems, but also their integration in the international science system.
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Keywords: Scientific productivity; Scientific competitiveness; Science policy

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0040-1625/$ - see front matter © 2007 Elsevier Inc. All rights reserved.
doi:10.1016/j.techfore.2007.02.013

1. Introduction

Economies across the world increasingly rely on knowledge to achieve sustainable growth and competitiveness in global markets. Therefore, it is not surprising that knowledge generation through formal learning processes such as research and development has intensified, and the ability to produce it is increasingly recognized as critical for any economy [1]. For example, a dramatic increase in paper publications and citations has been widely acknowledged as an indicator of this trend [2]. Both codified and non-codified knowledge are essential parts of these knowledge generation processes: codified knowledge facilitates diffusion and non-codified knowledge residing in each individual allows him or her to understand and enable the use of the former. The published scientific literature represents a particular but vast array of codified knowledge that can be easily diffused, absorbed by institutions and firms, stored or recorded for future use. It also provides an important indication of what and where is leading edge research being performed [3,4].

The centrality of knowledge, and the production of codified knowledge in particular, has made it a subject of interest for governments and the private sector alike [5]. As a result, there is an increased production of reports focusing on research and development (R&D) that aim at assessing knowledge ability and potential at international, national and regional levels [6]. International agencies such as OECD or the EUROSTAT, and national agencies such as the National Science Foundation have developed an array of indicators mapping knowledge and establishing science and technology performance comparisons across countries and regions. Yet, while these reports focus on a variety of issues associated to national or regional science and technology (S&T) systems, they typically consider publication data based on aggregate absolute numbers and their trends over time. For example, the most recent European Commission Key Figures report mentions European Union supremacy in publications over the United States but does not perform any more detailed analysis on the nature of these differences in scientific output [7]. The same is true for the most recent innovation scoreboard report [8]. Few reports carry out a more in-depth assessment, even at the country level. One report that does provide a fairly in-depth view of Australian science output and impact in an international comparison was developed by the Australian Bureau of Industrial Economics (BIE) [9]. May's [10] benchmark paper reporting that the UK had the most cost-effective scientific base among G7 countries draws extensively from that report. A set of other benchmark papers looking at countries with the strongest worldwide scientific production [11], or developing countries [12] have since been published. Much more recently, the UK Office of Science and Technology (OST) concluded a report to evaluate the UK S&T performance [13] that is also much more detailed in terms of looking at the various scientific areas. This report supplied the data for a critical paper published in the same year [14].

This research is inspired by the BIE and OST reports, but rather than a country, the analysis will focus on the competitiveness of the European Union and United States in science capability and quality. The interest of focusing on these two major scientific powers is obvious: In the last decades they accounted for around 72% of all international scientific output. Moreover the general results from the latest European Union Key Figures report [7] suggests that European Union publication output in international journals surpassed the one of the United States for the first time, though still behind in citations. Despite this important observation, little is known about the nature of this evolution in these two regions and, in particular, which scientific fields are driving these two blocks' overall publication and citation trends. This paper analyzes the scientific evolution of these two blocks in terms of scientific production, quality and visibility, looking at the detail of all scientific fields. First, we analyze the two blocks' trends in scientific impact, looking at the evolution of scientific fields in relation to the world. In a second part, we then focus on the scientific performance across countries within the European Union. For this analysis, scientific fields will be aggregated in scientific areas to facilitate the analysis. The last part of the paper presents conclusions. Before presenting the analysis, the next section details the methods and data.

2. Data and methods

To measure the quantity and quality of scientific output of a nation we use the number of published research papers and reviews, and respective citations provided by the ISI Thomson National Science Indicators On Diskette database (NSIOD-2003). Papers are defined as articles, notes, reviews and proceeding papers only and are attributed to a country as long as one of the authors is addressed to that country. The data was built using the global counting method[1] and thus the total number of papers does not reflect the real number of papers produced. Although we recognize Gauffriau and Larsen's [15] argument that a fractionated counting method is perhaps a more desirable counting method, Bourke and Butler [16] conclude that different counting methods produce little impact on the final outcomes. Since the database was built up by Thomson ISI based on a global counting approach, we are limited to this counting method. Each paper was also assigned a scientific field on the basis of the journal where it was published. In the database, each journal is assigned to one of 24 scientific fields as given in the NSIOD-2003 database (including a multidisciplinary field). When doing the analysis across European Union countries, these fields were further aggregated into the five fields proposed by OECD Frascati manual [17]. This aggregation excludes the multidisciplinary category. These five fields are: natural sciences, engineering, medical sciences, agriculture sciences and social sciences.

The NSIOD-2003 database covers the period 1981-2003, indexing approximately 5.900 peer-reviewed journals in the hard-sciences (hard-pure and hard-applied using Braxton and Hargens terminology [18]) and 1.700 in the soft-applied (social) sciences. The soft-pure sciences (arts and humanities) were not available in the database and therefore were not covered in the analysis. This Thomson ISI database has some recognized handicaps that can affect the analysis [19]. These include the various shortcomings identified by Chapman [20], including language bias [21], or the insularity of certain disciplines [22], often due to the fact that most disciplinary top journals are US based. Nevertheless, it takes into account the most significant journals in a wide range of areas of knowledge that exert a disproportionate influence in the world.[2]

An important note in the analysis of the paper is that the European Union is treated as being composed of only 15 countries. This is due to the fact that our analysis covers the 1986 to 2002 period, when only 15 countries were part of the European Union. When the focus goes from comparing the EU and the US to a comparison within the EU, Luxemburg is removed from the analysis because its number of papers and citations is extremely low and in some cases inexistent. Input data for the European countries is obtained through the OECD Main Science and Technology Indicators 2005/2 [24] and economic data is taken from the World Bank Indicators.[3]

[1] According to the information provided along with the database.

[2] Thomson ISI uses the Bradford Law of Scattering as a journal coverage strategy. This law asserts that the most influential and relevant research in a given field is concentrated in a relatively small number of journals (see [23]).

[3] This data was withdrawn from the World Bank Online Database, on the 2nd of April of 2006, from the following web address: http://web.worldbank.org/WBSITE/EXTERNAL/DATASTATISTICS/0,,contentMDK:20398986~hlPK:1365919~menuPK:64133159~pagePK:64133150~piPK:64133175~theSitePK:239419,00.html.

3. The knowledge race between European Union and the United States

The United States is clearly perceived as the world leader in science and innovation, with Europe behind. Yet, in a recent paper, King [14] showed that, in the middle of the 1990s, the European Union overcame the United States in terms of scientific output, while still lagging in terms of impact, measured through citations. Fig. 1 represents the evolution of publications and citations for the two regions, where it can be observed the EU15 overcoming the US in scientific output and closing the citations gap. In this section we will explore and deepen these results using several measures, not only related to the production of knowledge, but also associated to the impact that this knowledge is having on the international scientific community.

One of the most established measures of performance is the share of total papers and citations in relation to the world [13]. Although crude measures, both publication and citation shares provide a valuable insight as to systems capability, visibility and quality. In the period 1998–2002, the share of world publications was 37% for the EU15 and 34% for the US. Yet, the publication leadership by the EU15 is the product of a recent change. In fact, during the 1993–1997 period, the EU15 had 35% of world publications, against 37% for the US; and in 1986–1992, these figures change to 32% and 39% respectively. Together, these two blocks represent a quite stable share of the international scientific production along these periods, around 72%. In the share of citations, EU15 has been approaching US values since 1986–1992, but a considerable distance still exists. In 1998–2002 together they accounted for 89% of the world citations, although the US represented 50%, while the EU15 only 39%.

But aggregate values for publications and citations can sometimes hide important imbalances across fields of knowledge. Although publications are a fundamental process to communicate and exchange knowledge across all fields of science [25], each field has a well defined publication and recognition culture [26,27]. One of the most obvious differences is the rate at which papers are produced and citations generated. Table 1 represents the percentage of papers generated by each scientific field in relation to the total scientific production in the period 1998–2002. It is easy to observe that the output of scientific fields range from a maximum of 21.6% of total publications for clinical medicine to a minimum of 0.23% in law. A similar situation can be observed for citations, where there are substantial differences across scientific

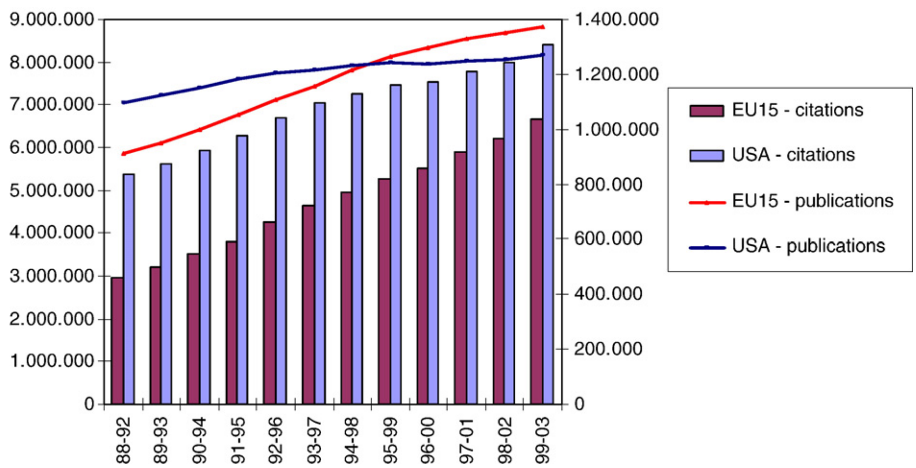

Fig. 1. Evolution of the publications and citations of the EU15 to the United States, 1988/1992–1999/2003.

Table 1
Scientific fields publication and citation differences, 1998–2002

Scientific fields	Publications (percentage scientific field to total fields) (%)	Citations (percentage scientific field to total fields) (%)
Agricultural sciences	2.07	1.02
Biology & Biochemistry	6.94	12.43
Chemistry	12.41	10.66
Clinical Medicine	21.60	23.87
Computer Science	1.07	0.28
Ecology/Environment	2.32	1.69
Economics & Business	1.30	0.50
Education	0.33	0.07
Engineering	7.13	2.36
Geosciences	2.56	2.04
Immunology	1.61	3.98
Law	0.23	0.13
Materials Science	3.43	1.58
Mathematics	1.75	0.51
Microbiology	2.04	3.23
Molecular Biology & Genetics	2.77	8.41
Multidisciplinary	1.45	1.29
Neurosciences & Behavior	3.57	6.48
Pharmacology	1.97	1.98
Physics	11.12	9.14
Plant & Animal Science	5.52	3.60
Psychology/Psychiatry	2.44	1.78
Social Sciences, general	3.23	1.22
Space Science	1.12	1.75

Source: Thomson ISI.

fields. Citations range from a minimum of 0.07% of the total for education, to a maximum of 23.87% again in clinical medicine. Although Table 1 only shows the positioning of the scientific fields for the 1998–2002 period, our calculations[4] lead us to conclude that this positioning is quite stable over time in both publications and citations. Yet two scientific fields were the exception: the share clinical medicine citations grew by 3.99% and Biology and Biochemistry declined by 3.39% from the period of 1988–1992 to 1998–2002.

These differences in papers published or citations received do not mean that a given scientific field is more relevant, or that it has more quality than any other fields. The average citation per paper for each scientific field clearly indicates this. For example, clinical medicine has the highest share of both publications and citations, but each paper received on average 4.76 citations during the period 1998–2002. By contrast, a scientific field such as immunology, with much lower shares of total publications or citations, had an average of 10.65 citations per paper. These features, to which others such as article life-time[5] could be added, are strongly embedded in social structures, congregating sets of behaviors, assumptions and

[4] Not displayed on the paper.

[5] If one takes into account the mortality statistics of publications, significant differences can be identified, as the life span of papers range from 10.5 years in Mathematics, to 5.2, in Mechanical Engineering, or 4.6 in Physics [29].

attitudes that are reinforced and articulated through repeated practices among scientists from the same scientific domain [28].

Hence, to analyze the differences between fields in the two blocks, we will use two different measures of performance based on existing analysis of the Australian scientific performance [9]. The first measure is known as Revealed Comparative Advantage. The Revealed Comparative Advantage (RCA) for country i and area j is calculated using the following formula, where Pij refers to the number of papers in the country, block or region in a scientific field, k is the total of scientific fields and N is the total of countries:

$$\mathrm{RCA}_{i,j} = \left(P_{i,j}/\sum_{c=1}^{N} P_{c,j}\right)/\left(\sum_{f=1}^{k} P_{i,f}/\sum_{c=1}^{N}\sum_{f=1}^{k} P_{c,f}\right)$$

This measure refers to the share of total world papers for a region or nation in a given field relative to the share of world papers produced by that nation in all fields or, equivalently, as the share of a country's papers in a given field relative to the share of world papers in that field. The premise that underlies this measure is that a block or a country that has a high revealed comparative advantage in a field is expected to have dedicated a higher proportion of resources to that scientific field, thus obtaining a relatively high level of output. This measure has some limitations as well. First, there is an inherent linear reasoning behind the measure. Second, scientific systems do not function as open markets, but rather according to national social, economic and scientific priorities. Therefore resources are not necessarily devoted to the scientific fields with the greatest potential for output or scientific return. Nevertheless, we believe that the metric provides a more refined analysis of the two blocks' scientific production strengths and weakness across scientific fields.

Fig. 2 shows the EU (a) and US (b) revealed comparative advantage in three distinct periods: 1988–1992, 1993–1997 and 1998–2002. As it can be observed, in 1998–2002, the most recent period in our analysis, the US had a higher RCA in 14 scientific areas[6] when compared to the world average, while the EU15 was ahead in 10 scientific areas. The US has an especially high RCA in all social sciences fields, but also in immunology, molecular biology, neurosciences and space science. The extremely strong RCA for law is explained by factors associated to the litigation culture of the North American society and the existence of a large national demand for law related publications [30]. Looking at Fig. 2(a) and (b), one can observe several scientific fields where the US has a lower RCA in relation to the world when compared to European score for this same field. This is true for in chemistry, physics, pharmacology, materials as well as space sciences.[7]

When looking at the evolution over the three periods presented in Fig. 2, it can be observed that the US RCA increased in ten scientific fields, stabilized in three and decreased in eleven. The relatively modest growth of revealed comparative advantage of clinical medicine in the US is especially surprising because the R&D budget of the National Institutes of Health has been increasing at a fast rate during the last decade and is nowadays the main federal source of funding for university research in the US [32]. Some of the decreasing

[6] In other words, this means that, in 14 scientific areas, the US has a greater share of total published papers than the fields' world's total share of papers (world base), one area equals the world base, and the others are below the world base.

[7] While the EU15 is higher than the US in RCA for space sciences, the scores for both blocs are above world average. This is explained by the fact that world scientific production in space sciences is highly concentrated in these regions — the two most important world agencies exploring space, the National Aeronautics and Space Administration (NASA) in the US and the European Space Agency (ESA) in the European Union (see for example Ginzberg et al. [31]).

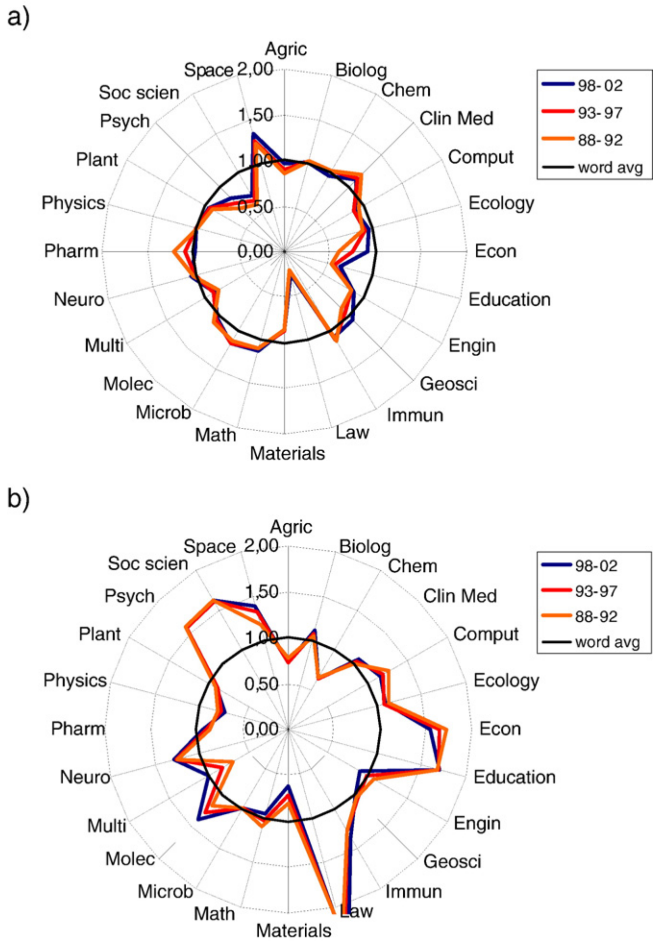

Fig. 2. Revealed comparative advantage for USA and European Union compared to the world. Note: a) European Union 15 countries; b) United States of America.

fields such as engineering and mathematics dropped below the world average, joining fields such as agricultural sciences, chemistry, materials science, microbiology, pharmacology, physics and plant and animal science, which have been below world base levels during all periods considered in the analysis. During the same periods, the EU15 RCA grew in seventeen scientific fields and decreased in seven. While the EU15 has had ten scientific fields with a RCA above the world base over the periods considered in the analysis, there have been changes in the composition of this group. From 1988–1992 to 1998–2002, pharmacology and chemistry dropped below the world average, while geosciences and physics climbed above.

When looking at the RCA of the various fields of knowledge, it is also possible to take into account the data of Table 1, thus incorporating the relative publication weight for each field. We start doing this analysis by focusing on the evolution trend of scientific fields whose individual weight in world publications is above 5%. This group is composed by clinical medicine, chemistry, physics, engineering, biology and biochemistry and plant and animal science, representing around 65% of total publications in a given period. Any substantial change in this group of fields can easily push a block performance up or down. We have analyzed trends in this group for the two blocks by multiplying the change in each scientific field by its respective weight[8] and adding them together to get a final result. The results show that this group was not responsible for the change in overall trend of publications between EU15 and the US as from 1988–1992 to 1998–2002, the EU15 decreased 1.48% while the US decreased 1.15%.

We then considered an alternative approach, analyzing scientific fields that grew above 10% RCA between 1998–2002 and 1988–1992. We conclude that EU15 had eight scientific fields[9] in this group, including agriculture, economy, education, geosciences, law, psychology, social sciences and space science, which corresponds to a 13.28% share of the total publications. By contrast, the US had only four[10] fields in this group, corresponding to a mere 5.57% share of total publications. If the same analysis is performed for scientific fields that declined at a rate equal to or higher than 10%, then the EU15 has only one scientific field[11] in the group, corresponding to a share of 1.97% publications, while the US has four scientific fields[12], including law, molecular, multidisciplinary, and space sciences, that together correspond to a share of 13.61%. These changes appear to be decisive in the switching of the positions of the US and the EU15 in terms of overall publication. This result leads one to conclude that the growth in more scientific fields and, especially, the difference among the two blocks in the relative importance of the few fields that either grew or declined at rates equal or above 10%, were the critical drivers for the EU15 overcoming the US in the volume of scientific productions. By contrast the evolution of the group of scientific fields with greatest share of production appears to have had little impact in the overall trend.

A second measure of comparative advantage can be obtained looking at relative citation impact. The Relative Citation Impact (RCI) is the ratio between citations and papers for a given field in a region in relation to the citation and papers of the same given field in the world for a given period. This is an important indicator of visibility and quality of a determined field of science. State agencies [9] as well as researchers [10] often use this measure while performing bibliometric studies because these indicators correct for differences in both citation and publication characteristics among scientific fields [33]. The Relative Citation Impact (RCI) for country i, area j, in time period t, was calculated using the following formula, where N refers to the total number of countries:

$$\mathrm{RCI}_{i,j,t} = \left(C_{i,j,t}/P_{i,j,t}\right)/\left(\sum_{c=1}^{N} C_{c,j,t}/\sum_{c=1}^{N} P_{c,j,t}\right)$$

This measure adds visibility and quality components to the scientific RCA analysis of each region. Fig. 3 shows the results for the US and EU15 regions, for the 1998–2002 period (in the formula i refers to the regions – US and to the EU15 – and t to the period 1998–2002). First, in terms of visibility and quality as measured by the RCI, one can easily observe that all US scientific areas are above the world base. By contrast, the EU15 has 11 out 24 scientific fields below the world base, although 8 of these areas are very near the average. The only scientific area where EU15 is considerably below world citation average is law, mostly due to the overwhelming prominence of the US in this field. These figures suggest that US scientific production is not only more visible than the European one as a whole but also individually across most fields. Even in fields

[8] The scientific field weight corresponds to the scientific field share in the world of total papers produced by all scientific fields in the world.

[9] These scientific fields are: agriculture sciences, economy, education, geosciences, law, psychology/psychiatry, social sciences and space sciences.

[10] These scientific fields are: law, molecular biology and genetics, multidisciplinary studies, and space.

[11] This scientific field is: pharmacology.

[12] These scientific fields are: economy, engineering, materials and mathematics.

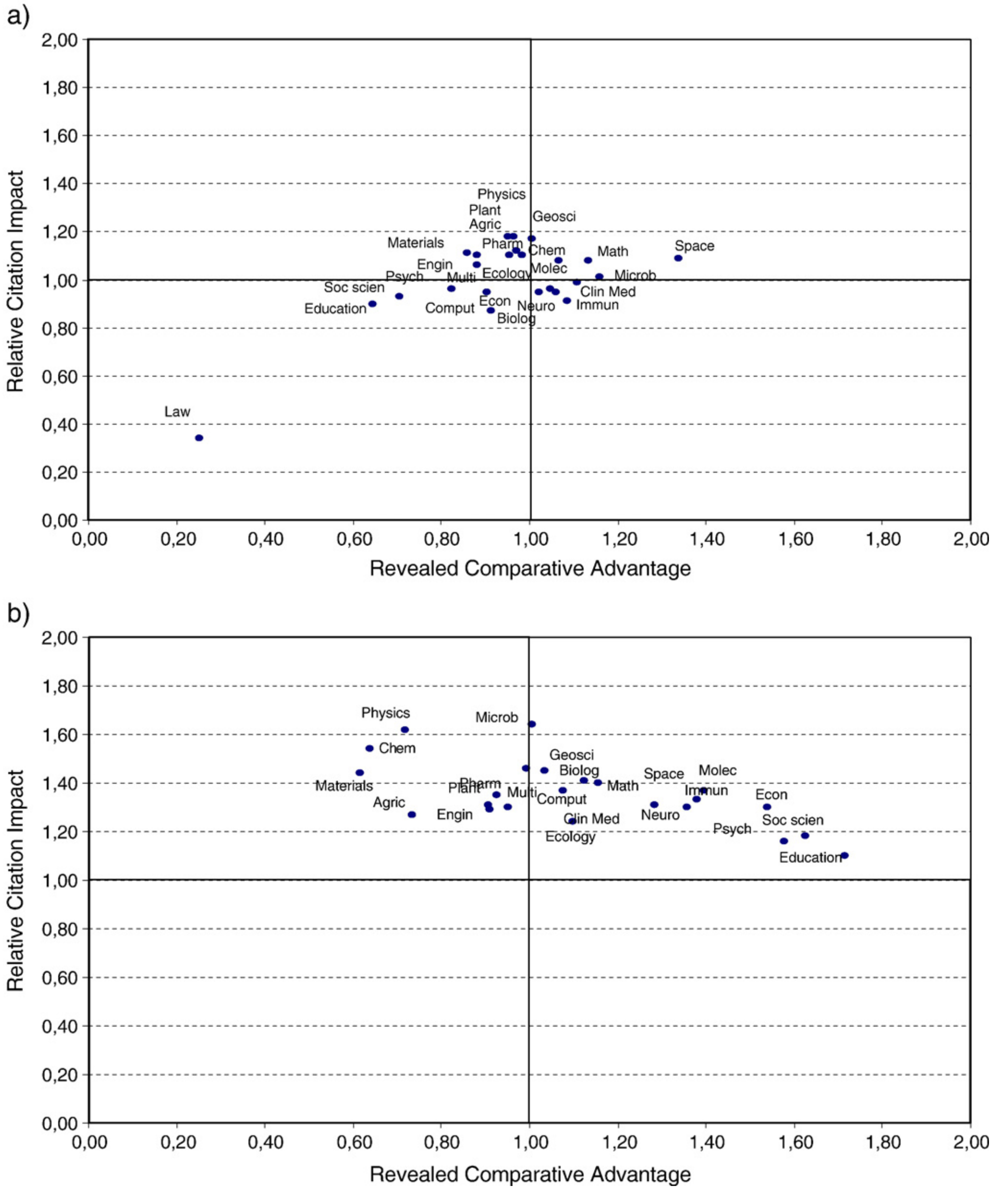

Fig. 3. Relation between revealed comparative advantage and relative citation impact, 1998–2002. Note: a) European Union 15 countries; b) United States of America.

where the US contribution (in paper production) is well below the world base, their quality is still quite higher than the base. This suggests that the US scientists publish more frequently in top journals, thus receiving a higher number of citations. While these results may reflect an intrinsic higher quality of US science, they can also be influenced by factors such as the dominance of English language in top scientific journals ([34,35], favoritism [36], editorial preference for certain theoretical and methodological approaches [37], as well as incentives to publish in high impact outlets [34].

Although our data does not allow us to test directly these hypotheses, a recent paper by Sheldon and Holdridge [38] has looked at dominance of publications in the leading technical journals. The authors showed that, in 1991, the US dominated the leading journals in 17 out of 20 fields of science, while the EU led the remaining three fields. Yet, they also find that this situation seems to be changing. The analysis revealed that, by 2001, the EU already dominated the leading journals in 12 fields while the US only dominated 7[13]. In fact, as the analysis below shows, there is a progressive improvement in the EU15 RCI which is in line with Sheldon and Holdridge's conclusions [38].

To understand the evolution of both the revealed comparative advantage and the relative citation impact of the two blocks, we look at the change in both RCA and RCI measurements between the periods of 1988–1992 and 1998–2002. The first measure, which assesses the change in the relative quality in relation to the world base, is calculated as follows:

$$\Delta \mathrm{RCI}_{i,j} = \log(C_{i,j,98-02}/P_{i,j,98-02})/\left(\sum_{c=1}^{N} C_{c,j,98-02}/\sum_{c=1}^{N} P_{c,j,98-02}\right) - \log(C_{i,j,88-92}/P_{i,j,88-92})/\left(\sum_{c=1}^{N} C_{c,j,88-92}/\sum_{c=1}^{N} P_{c,j,88-92}\right)$$

The second measure that assesses the change in the revealed comparative analysis in relation to the world base is calculated through the following formula:

$$\Delta \mathrm{RCA}_{i,j} = \log\left(P_{i,j,98-02}/\sum_{c=1}^{N} P_{c,j,98-02}\right)/\left(\sum_{f=1}^{k} P_{i,f,98-02}/\sum_{c=1}^{N}\sum_{f=1}^{k} P_{c,f,98-02}\right) - \log\left(P_{i,j,88-92}/\sum_{c=1}^{N} /P_{c,j,88-92}\right)/\left(\sum_{f=1}^{k} P_{i,f,88-92}/\sum_{c=1}^{N}\sum_{f=1}^{k} P_{c,f,88-92}\right)$$

The data in Fig. 4 demonstrates that the relative contribution of the EU15 in terms of both paper output and international visibility has been increasing in most fields. While there are various possible explanations for this changing trend in European science, the one that seems most influential is the growing worldwide importance of impact factor measurement. This measure, strongly criticized by many authors for its use in purposes other than ranking scientific journals [34,39], has become a main feature to decide upon hiring processes, granting tenure and assuring grants and other research funds not only in the United States where it started but also in European and Asian countries [40]. A growing importance of impact factors for university promotion in Europe, is urging European scientists to publish in leading journals characterized for having high impact factors [41,42].

Yet, the overall gains in visibility in relation to the world are very small. This results from the fact that visibility gains have been mostly achieved in fields which represent low shares of the total number of citations, such as economy, law, education, social sciences, or agriculture sciences. At the same time, fields with higher shares of total citations, including immunology, molecular biology, biology and biochemistry, physics and neurosciences have lost impact in relation to the world. The weight of the latter scientific fields seems to be enough to pull the overall quality result close to a standstill.

The change in US scientific performance presents a much more blurry picture. The US overall contribution to international science basically stabilized *vis a vis* the world, although decreasing slightly

[13] The Asia Pacific region dominated in the remaining scientific field.

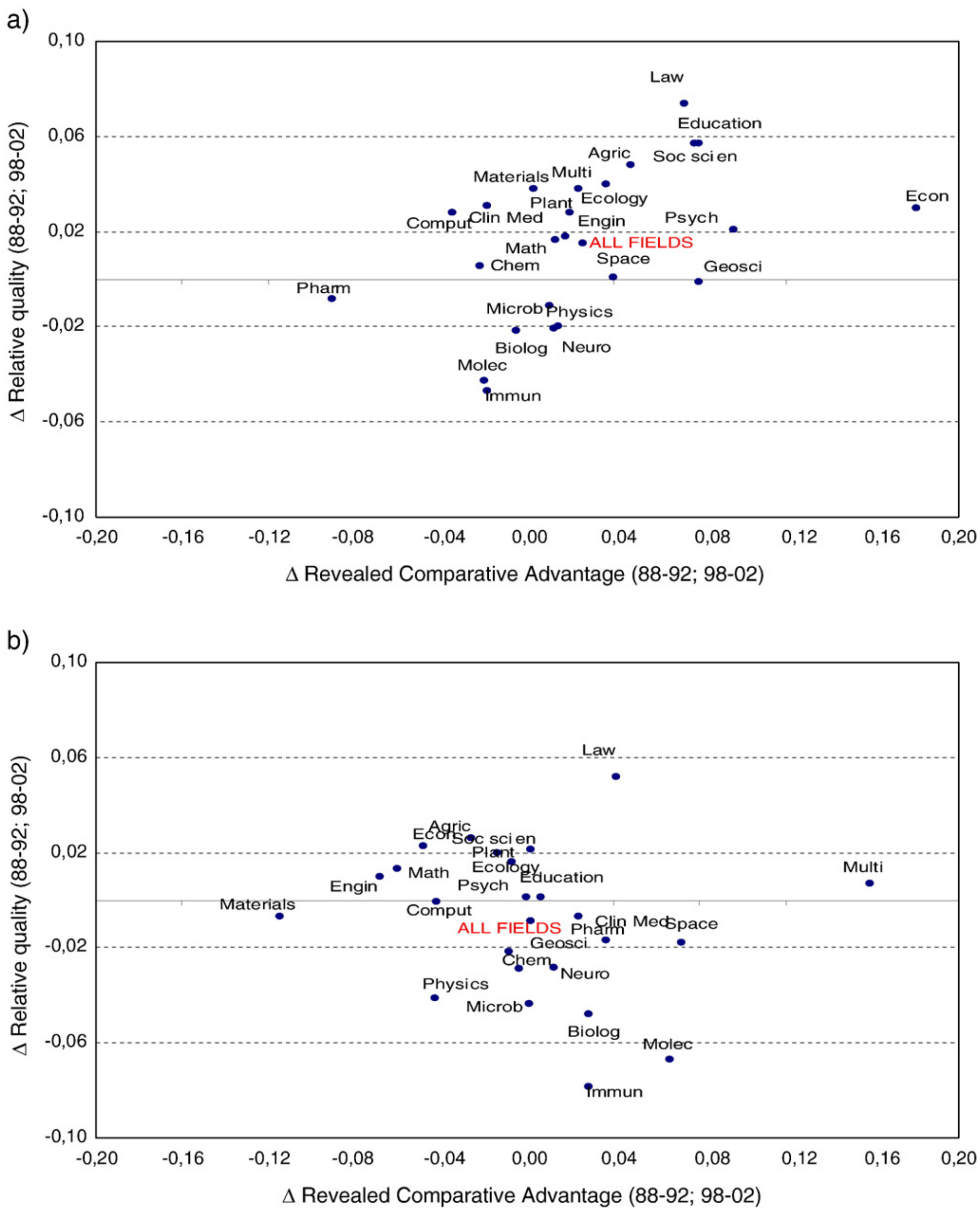

Fig. 4. Structural change and quality in EU15 and USA science systems. Note: a) European Union 15 countries; b) United States of America.

its quality[14]. This is the result of a conjunction of trends across scientific fields. As it can be observed in Fig. 4, most fields that increased their scientific production in relation to the world did not witness an

[14] The change concerning all scientific areas of both the US and EU15 is calculated using a simple mean. It corresponds to the sum of the change of all scientific areas divided by the total number of areas.

equivalent increase in quality; on the contrary, they significantly decreased their quality. Fields with a high contribution in terms of overall citation rates, including biology and biochemistry or molecular biology and genetics, are among those which decreased their visibility/quality in relation to the world base. Because of their high citation rates, their decline in relative quality had a very significant negative impact on the overall impact trends. Conversely, there is a group of fields, including agricultural sciences, computer science, ecology, economy, engineering, mathematics, physics, as well as plant and animal sciences which, despite a decrease in relative output, have reinforced their relative quality.

Given the observations noted above, and following Price's [43] theory of scientific growth, one can argue that the scientific system of the EU15 is in an "adolescence" phase when compared to the US which, according to the same theory, would be in a maturity state. The absolute EU15 scientific production is rising considerably in relation to the world base when the US system scientific production is equal to the growth of the world base. However, our analysis also suggests that characterizing the status of the scientific system based only on overall levels and trends of scientific production can be reductionist and provide very limited information as to understand what is being observed. In the context of an increasing complexity and continuous fragmentation of science [44], as well emerging modes of research strongly emphasizing multidisciplinary collaboration [45], it becomes critical to take the scientific fields' evolution into account. The analysis by scientific fields presented above enables one to perceive which scientific fields drive the evolution of the overall production, as well as to better understand the evolution of the production in relation to the characteristics of the scientific system and the evolution of the institutional setup of the economy [46]. This latter dimension will be particularly explored in the next section.

4. What is happening in Europe?

The growth of scientific production and visibility in Europe in relation to the US calls for further investigation of who is producing what within the European Union[15]. Fig. 5 displays the evolution of published papers and citations for each EU15 country in relation to the other. During the relevant period, EU countries with large and consolidated scientific systems, including France, Germany and the UK, have consistently been above the EU15 mean. Nevertheless, one can observe a slight convergence path among countries both on publications and citations, with the leading countries reducing their share of paper production and citations in relation with the other European countries. The case of the UK is particularly relevant because, during the 1986–2002 period, this country showed a negative 1.74% compound annual growth rate[16] (CAGR) in citations and a negative 1.53% growth in publications relative to the rest of the EU15 (the absolute number of papers and citations is growing). It was the country in which relative publications rates declined the most since 1988[17], though the compound annual growth rate of citations of Sweden declined at a faster rate (−2.54%). The other country where both relative citation and publication declined was France, although the annual decrease rates were negligible (−0.51% in citations and −0.45% in

[15] The database does not include publications by the different US States, which prevents an equally interesting analysis of the US regional dimension.

[16] The compound annual growth rate is a method of assessing the average growth of a value over a specific time. It is calculated by taking the nth root of the total percentage growth rate, where n refers to the number of years in the considered period. The Compound annual growth rate can be calculated using the following formula: $\mathrm{CAGR}=(A/B)^{(1/T)}-1$, where A refers to the ending value, B to the beginning value, and T the number of years between the beginning and the ending value.

[17] The UK was the country which declined the most in terms of paper share and the presented the second highest decline in the citation share.

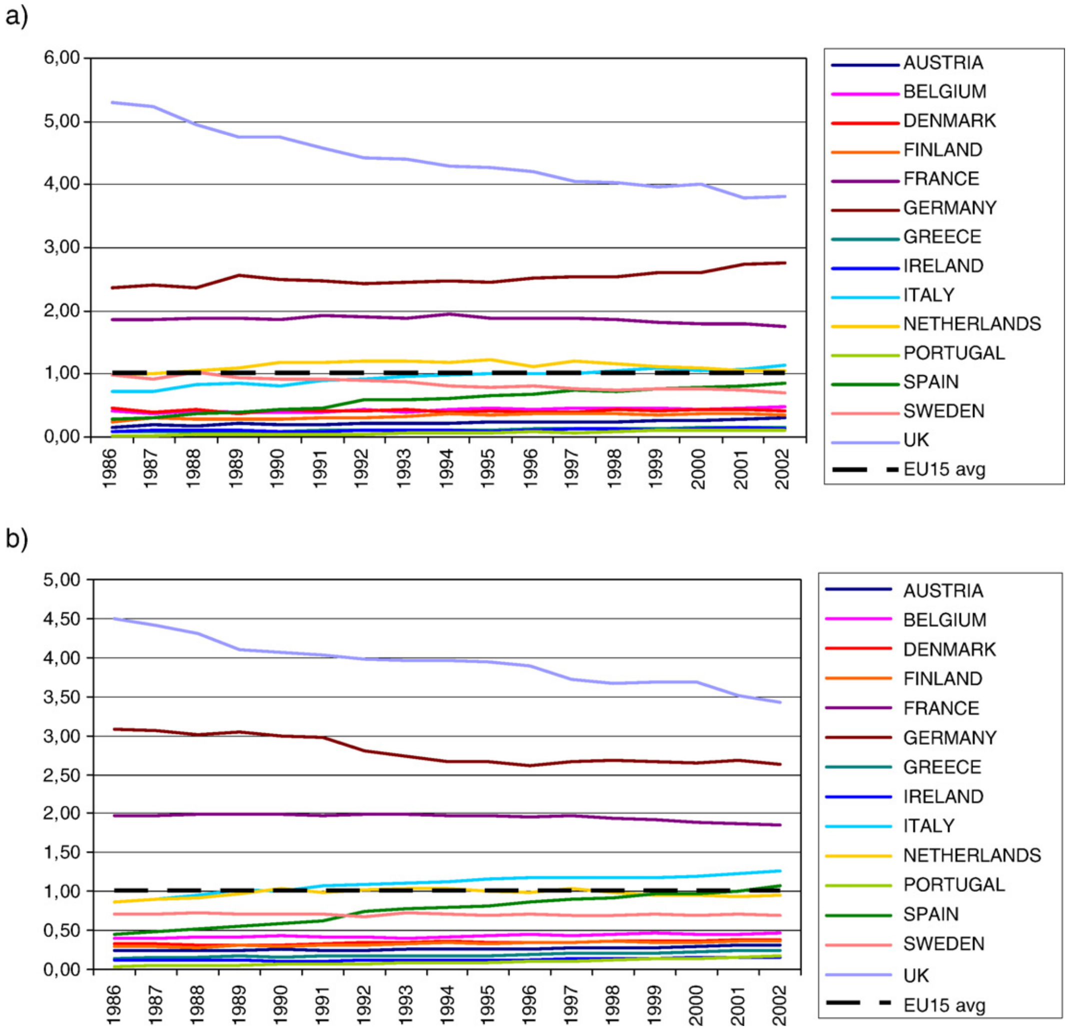

Fig. 5. Evolution of European Union countries in terms of citations and publications in relation to the European Union average, 1986–2002. Note: a) Evolution of citations in relation to the European Union average; b) Evolution of publications in relation to the European Union average.

publications). In this respect, Germany is the only country of this group that grew in the share of relative citations. The scientific system of countries such as the UK can be characterized as in a mature phase [46] because, although their number of publications and citations is still rising, the remaining European countries are growing at a faster rate than them, leading to a decline in both shares of publications and citations.

This relative decline also reflects the accelerated growth of countries with a reduced world share of publications and citations such as Portugal, Spain or Greece in relation to countries that have traditionally been economically and scientifically prominent. The compound annual growth rate of relative scientific output and impact for these countries with a smaller science base has been quite impressive. Portugal's CAGR for this period was of 9.68% in citations and 8.50% in publications. Spain, the country with the second highest growth, had a growth of 5.78% for citations and 4.93% for publications. However, as Fig. 5 demonstrates, the performance of these countries in both citations and publications is still well below EU15 average. Taking Price's [47] lifecycle characterization of the scientific systems, one can argue that these systems are clearly in the infant period of development: their number of publications and received citations is low, but they grow faster in both accounts because their starting point is low and already supported by a mass of existing international knowledge [48]. Within the catching up group, figures for the share of papers and citations associated to Spain and Italy suggest these countries have recently entered the group of countries above the EU15 mean.

In addition to overall output and impact, our understanding of the EU patterns would not be complete without looking at the scientific structure across fields. First, we look at the narrowness or breadth of the scientific structure. This indicator represents the level of scientific specialization within a nation, thus providing valuable information regarding the use of resources and the establishment of scientific priorities. To determine the scientific structure of a country we followed three steps. First we changed the RCA formula from what is presented on page 6 so that, instead of analyzing the paper production of a block in relation to the world, we can analyze the paper production of each given country in relation to the aggregate EU15 for the 1998–2002 period. The resulting formula is displayed below:

$$\mathrm{RCA}_{i,j} = \left(P_{i,j,98-02} / \sum_{c=1}^{EU15} P_{c,j,98-02}\right) / \left(\sum_{f=1}^{k} P_{i,f,98-02} / \sum_{c=1}^{EU15} \sum_{f=1}^{k} P_{c,f,98-02}\right)$$

Second, we obtained RCA results for each scientific field. The last step was to calculate the variance of the RCA results for the twenty four scientific fields for each country, thus obtaining the specialization level. The more the result approaches zero (zero indicates that a country field share equals exactly that of the average of the EU15 — no variance) the broader the system is. The normalization of each country shares with the EU15 shares enables one to take into account the underlying breath and relevance of some fields.[18]

The results, presented in Fig. 6a, are not particularly surprising, except for the UK. The fact that countries such as Portugal, Ireland, Greece or Spain are among the ones with a narrower scientific structure is typical of countries that are still developing their scientific base [9]. These countries, not only have less resources than others to devote to science and technology, but they are also typically forced to adopt scientific policies that are based on the country's social and economic priorities. At the other end of the spectrum are countries with a broad structure, such as Sweden, Finland, Germany, or France, all of which have expenditure on research and development as a percentage of the GDP above the EU15 average. As a result, they have enough resources (capital and human) to invest in a vast portfolio of research fields that potentially increase the scientific and technological capabilities and options available for these countries [48,49]. According to Bourke and Butler [16], one of the main benefits of having a broad scientific structure is related to flexibility, something critical within a scientific development that has become increasingly unpredictable. The distributed knowledge base across several scientific fields also enables countries to better develop complex knowledge that requires multidisciplinary effort such as Biotechnology or Nanotechnology [45].

In this framework, Denmark and the UK are the exceptions. Denmark has one of the biggest expenditures in research and development in relation to the GDP in Europe, yet keeps a scientific structure that is narrower than other countries that invest as much (or even less) in science. When looking at the

[18] For a detailed explanation of this measure see [9].

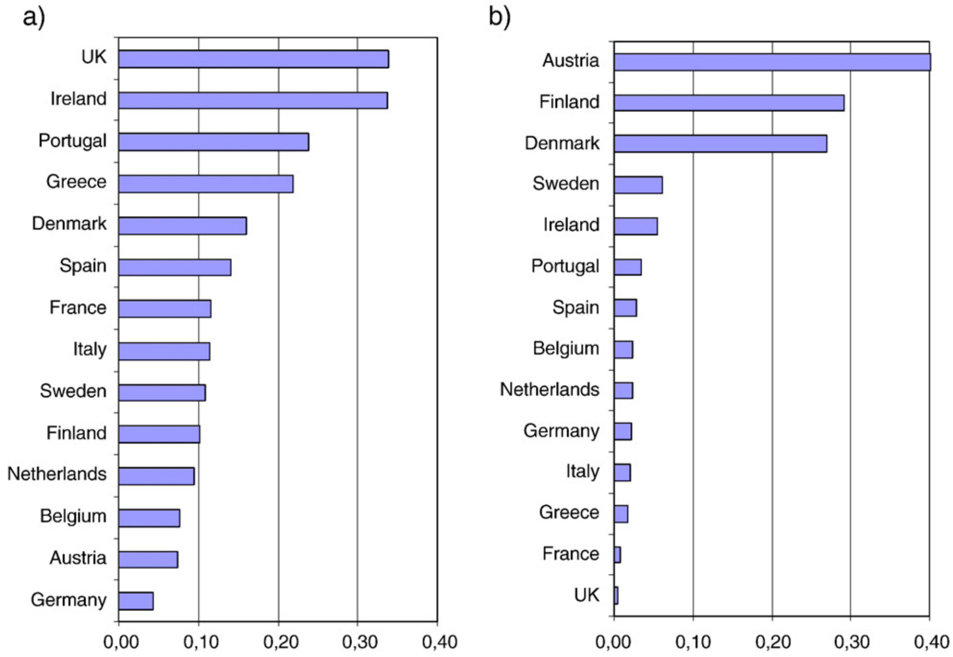

Fig. 6. Specialization and evenness of quality in the European Union countries, 1998–2002. Note: a) Scientific specialization; b) Scientific quality and visibility equity.

scientific areas, the narrower structure can be explained by a strong investment in plant and animal sciences, biology and biochemistry, as well as agricultural sciences. These scientific areas each have above 50% more scientific production than the average EU15. The investment in biology and biochemistry is seen as a need to search and consolidate niches in the biotechnology sector, while the investment in the agriculture sciences and plant and animal sciences is related to its traditional innovation system, still strongly based in dairy products [50]. Nevertheless, the investment in these areas enables the country to be one of the countries in the forefront of biotechnology domain [51]. The UK is the nation where we see a clear specialization pattern. This specialization skews towards the soft-sciences. While the other scientific fields' production are generally around the EU15 average, the British scientific production in the soft-sciences greatly surpasses the EU15 average (in education the UK produces 1.8 times more, in law 1.5 times more, in social sciences general 1.3 times more, in economic and business 76% more and psychology/psychiatry 58% times more than the EU15 average).

The development of the scientific structure can also be apparent in the evenness or unevenness of quality across scientific fields within the same country. To determine the scientific visibility unevenness across areas in a nation, we apply the three step routine used for calculating the scientific specialization of a country, but instead of using the RCA formula, we use the RCI formula as displayed below:

$$\mathrm{RCI}_{i,j} = \left(C_{\mathrm{COUNTRY},98-02}/P_{\mathrm{COUNTRY},98-02}\right)/\left(\sum_{c=1}^{K} C_{\mathrm{EU15},98-02}/\sum_{c=1}^{K} P_{\mathrm{EU15},98-02}\right)$$

As with the specialization routine, the countries scientific unevenness across areas in a nation is the result of the variance for the same twenty four scientific fields. Basically, evenness or unevenness in quality is given by comparing variance across different fields in the same country. One point should be made clear while looking at this measure: it only indicates that there are differences of quality and international visibility across scientific fields. A more even quality structure across fields does not mean that one country's scientific quality is better or worse than any other country. Instead, it means that there are not substantial quality differences across scientific fields in the same country when compared to the EU average.

Fig. 6 (part b) indicates that three European countries have a large variance across scientific fields. Austria presents a disproportionate unevenness among scientific fields, much of it explained by a strong relative citation in scientific fields such as molecular biology and genetics, immunology, neurosciences and behavior, as well as biology and biochemistry, together with very weak relative citations in education, computer science, mathematics and engineering. This imbalance across areas in a country such as Austria, characterized by a broad system in terms of overall output, suggests that their effort to have an even distribution of resources (which is more closely tracked by paper output), is not being efficient in terms of associated quality or impact. There are two other countries that stand out in terms of scientific unevenness: Denmark and Finland. This result is to a certain extent explained by strong relative citations in unexpected areas, including education (Denmark) and law (Finland).

The UK situation is inverse to that of Austria. In the UK, although resources are unequally applied, the scientific areas present a remarkable similar quality and visibility. This suggests that some scientific areas may be very efficient, producing quality science with few relative resources when compared to other more endowed areas. Yet, understanding situations such as the UK or Austria can be beyond a matter of resources. Another important aspect is the greater or lesser integration of some scientific areas of a country in international science. The fact that the UK is deeply integrated in most scientific fields in the world can help explain this country's position [14]. The accumulated knowledge and consolidated position may enable scientific areas with fewer relative resources to have a level of quality and impact similar to others absorbing greater resources. The same rationale may be valid for Austria. It is possible that the integration in the international science framework is limited to a few already mentioned scientific fields, while the other areas have not integrated as well yet.[19]

When analyzing Fig. 6 a) and b) together, the most evident fact is the mixed picture: countries with narrow (e.g.: Greece) and broad (e.g.: Austria) scientific structures show a great variance of quality across national scientific fields. At the same time, countries with a broad (e.g.: Finland) and narrow (e.g.: UK) scientific structures show equally lesser variance in quality across scientific fields. Thus, the level of specialization of a country seems to be hardly related to the level of evenness or unevenness in terms of international quality and visibility. The level of R&D funding also does not seem to be the driver of the observed differences. There is no distinctive relation between countries with high or low levels of gross expenditure in R&D as a percentage of GDP and specialized or broad scientific structures, as well as uneven or even scientific quality.

Regardless of the degree of specialization in output and impact, it is still important to recognize that the international quality and visibility of each European country is different. Fig. 7 shows the impact of each EU15 country scientific field in relation to the world as measured through the RCI metric explained in page 8 of this paper. There are two changes to that formula, though. First, instead of relating a block to the

[19] The RCI measure show considerable imbalances among scientific fields in Austria transpiring a substantial difference regarding the integration and acknowledgment of individual scientific fields in the international scientific community. Some scientific fields have a well above EU15 RCI average, including molecular biology and genetics (6.68) or immunology (3.62), therefore showing a considerable visibility in the international scientific community; others such as computer science (0.33) or education (0.04) are well below EU15 average by individual scientific fields, therefore showing a very low acknowledgement by the international scientific system.

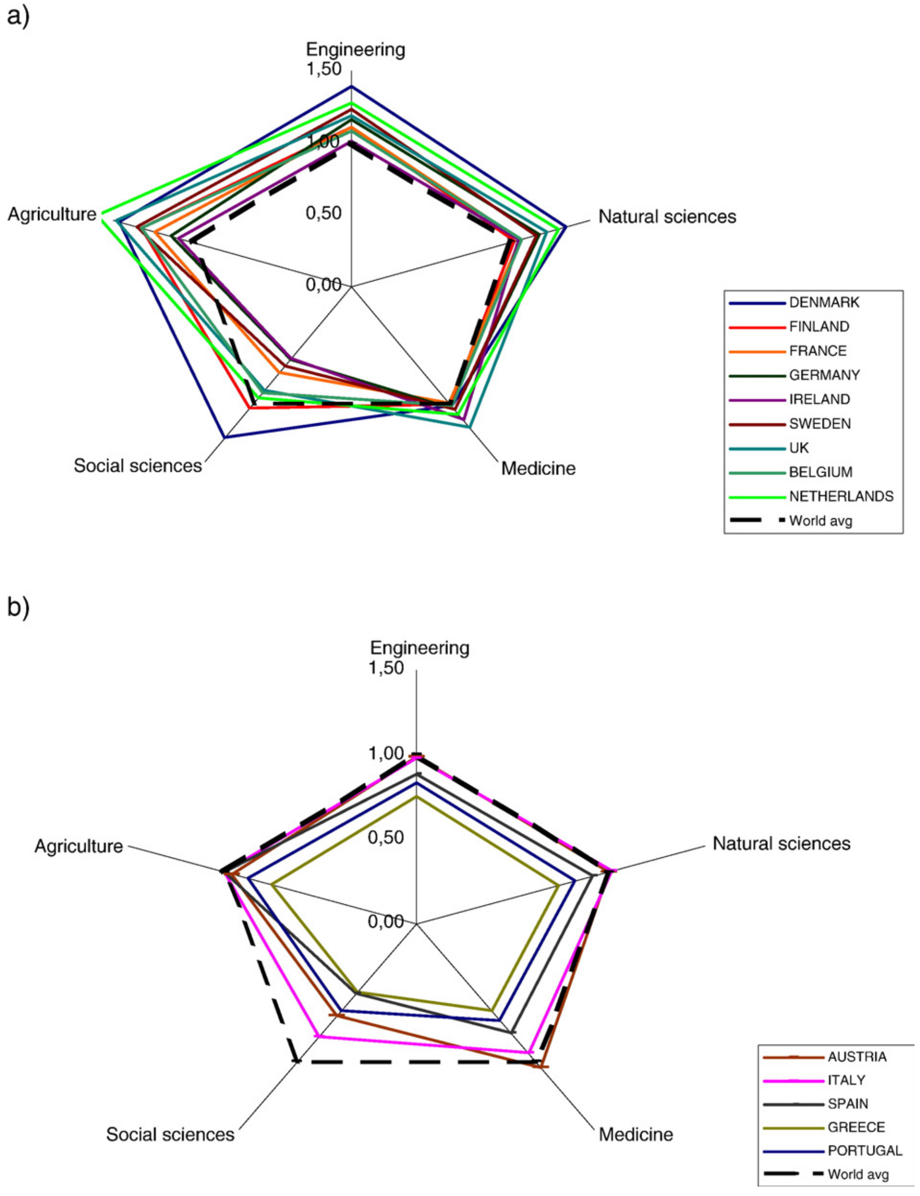

Fig. 7. Relative citation impact, EU15 countries, 1998–2002. Note: a) Countries with RCI above the world average in three or more scientific fields; b) Countries with RCI below the world average in three or more scientific fields.

world, we now relate each EU15 country to the world; and second, the twenty four scientific fields are aggregated into five fields as proposed by the Frascatti Manual [17] to ease presentation.

As seen before, whenever the value achieved by a country is higher than 1, then that country in that specific scientific field has an above world average impact; if it has a value lower than 1, then its impact is below world average. Based on this scale and aiming to achieve a better characterization of scientific performance among EU15 countries, they were divided into two clusters. One cluster consists of those countries that achieved an impact above world average in at least three scientific areas, while the other cluster has the countries with RCI below world average in at least three scientific fields.

As Fig. 7 (part a) indicates, the cluster of high performers, whose impact is above the world average in three or more scientific areas, is composed by small-sized high income countries, including those from Scandinavia and Benelux, with usually small shares of the world of total papers and citations, as well as by large countries with a rooted tradition in science and technology, such as Germany or France[20]. In this group the RCI of some of the small sized high income countries is also among the fastest growing in the EU15. From 1993–1997 to 1998–2002, Denmark was the third and Finland the fourth fast growing countries in terms of RCI, among all EU15 countries.

The cluster of low performers, with a RCI below the world average impact in three or more disciplinary areas (Fig. 7b), includes Austria and the Southern European countries. Yet, it is important to note that the overall position of Italy and Austria is driven by a very low performance in social sciences, with the rest of the areas having impact factors very near the world impact average. Moreover, their overall impact is growing faster than that of the other countries positioned in the first group of high performers. As a result, Italy and Austria are on the verge of joining the cluster of high performer countries discussed above. Portugal and Greece have all the scientific areas with a world average impact below average, while Spain fares slightly better, with an impact in agriculture sciences close to the world average. These countries can clearly be characterized as infant or adolescent countries in scientific terms. When compared to most of the other EU15 countries, they exhibit a weak impact performance, but also higher growth rates. In particular, the RCI growth of Portugal was the second highest of all EU15 countries, while the Greek was the fifth highest.

In sum, the EU15 shows a remarkable inequality on scientific quantity (papers produced), quality and visibility (citations and impact measures) among its countries. This inequality seems to be associated to the resources dedicated by each country to science and technology over time. Early investments in some countries facilitated the build up of a strong core of researchers in western European countries such as France, UK, Germany and, more recently, Scandinavia, leading them to achieve high levels of scientific production and visibility. In addition, it is important to stress the advantage resulting from the early investments in research and associated visibility in international journals [47]. This allowed the work of scientists in these countries to be internationally recognized and accounted for along the years, allowing them to consolidate their position within the international scientific community. But the analysis also shows that some of these countries are still growing their scientific base, in particular Finland and Denmark. As a result, they have great potential to further establish their position internationally. Finally, a set of countries, mainly from southern Europe, has traditionally shown less commitment to research and development [24]. As a result, they still lag in levels of publications and received citations [52]. Recently, this seems to be changing and we can observe spectacular growth by these countries in both scientific output and impact.

In this sense, comparing countries with high levels and low levels of absolute investment in research and development may not seem entirely fair [9]. For example, Price [47] argues that scientific production and citations are influenced by a country's population. Thus, we calculate and compare a series of benchmark ratios where the total number of publications and citations are divided by the size of country measured by total population, size of the labor force, as well as gross national income. The results are

[20] All countries with the exception of Sweden have the five areas with values above 0.90.

Table 2
Scientific performance adjusted for population and income, 2002

	Labor force		Total population		GNI	
	Citations	Publications	Citations	Publications	Citations	Publications
Highly above average	Denmark	Denmark	Denmark	Denmark	Denmark	Denmark
	Finland	Finland	Finland	Finland	Finland	Finland
	Netherlands	Netherlands	Netherlands	Netherlands	Netherlands	Netherlands
	Sweden	Sweden	Sweden	Sweden	Sweden	Sweden
Above average	Austria	Austria	Austria	Austria	Austria	Greece
	Belgium	Belgium	Belgium	Belgium	Belgium	Belgium
	UK	UK	UK	UK	UK	UK
Below average	France	France	France	France	France	France
	Germany	Germany	Germany	Germany	Germany	Germany
	Ireland	Ireland	Ireland	Ireland	Spain	Spain
						Austria
Highly below average	Greece	Greece	Greece	Greece	Greece	Ireland
	Italy	Italy	Italy	Italy	Italy	Italy
	Portugal	Portugal	Portugal	Portugal	Portugal	Portugal
	Spain	Spain	Spain	Spain	Ireland	

Note: Gross National Income (GNI) is a World Bank terminology. Its definition is the same as the Gross National Product.
Source: Thomson ISI NSIOD-2003; OECD, MSTI-2005/2; World Bank, World Development Indicators.

presented in Table 2, which places the countries in categories depending on their relative position to the average. Results show that Scandinavian countries and small sized populated countries from Western Europe such as the Netherlands and Belgium perform substantially above the average. The opposite trend happens in the largely populated countries such as Germany or France, which perform below average in all absolute indicators. Italy is different because it performs highly below average, exhibiting a performance trend similar to that of other Mediterranean countries. The UK is the exception of the group of highly populated countries since it is able to achieve performances above average in all indicators. Table 2 also shows that the group of countries included in Fig. 7b performs highly below average in almost all indicators, confirming the weak scientific performance identified in previous analyses, even when controlling for size. The exception to these countries is Austria. Austria is the only country of this group that has a performance above average in most indicators, with the exception of publications to the GNI, swapping positions there with Greece.

5. Discussion and conclusions

During the 1990s, in the midst of a significant increase in world scientific output, the EU15 overcame the US in paper production and is catching up in visibility and impact, as measured by citations. This perspective has been conveyed in previous reports [2] and papers [14]. Yet, existing work has not focused on trying to understand the role of the various scientific fields in this evolution. Our study show that, from 1988–1992 to 1998–2002, most scientific areas in the EU15 improved their production as well as their relative quality in face of the world average. Overall, the revealed comparative advantage increased moderately. In the same time frame, the US system stabilized its RCA, growing at the same rate as the world base. The US leads in terms of output in fourteen out of twenty four scientific fields, with the EU leading in the remaining ten. The US has a particularly strong scientific production in the social sciences, immunology, molecular biology, neurosciences and space sciences, fields that can be considered its major scientific strongholds. The EU15's major strongpoint is space science.

We also show that the reason for seeing the EU15 overcoming the US in scientific output can be explained by the unequal weight of a few scientific disciplines that led in terms of either substantial growth or decline, here considered as the 10% RCA mark. While the EU15 had eight scientific fields, corresponding to roughly 13% of all publications, growing above 10% from 1988–1992 to 1998–2002, the US only had four fields, which represented a weight of 6%. These fields are ecology, engineering, materials science and mathematics. At the same time, the US saw four scientific fields declining at a rate greater than 10%, a share of almost 14% of all publications. During the same period, the EU had only one field declining at such fast rate, corresponding to 2% of the total (the scientific field is pharmacology).

Nonetheless, despite the evolution of the EU15 in terms of total scientific production, the US is still the scientific system with greater international visibility and impact. The relative quality of the EU15 grew only slightly above the world base rate, while the US showed a slight decline in relative citation impact. Nevertheless, all US scientific fields have a relative citation impact that lies above the world mean, while the EU15 has 11 out of 24 scientific fields below the world base relative citation impact.[21] More important is the fact that the relative citation impact of all scientific fields is higher in every field for the US when compared to the EU15.

Within Europe, all countries are increasing their scientific capability (published papers) and quality (received citations). Yet, there are important differences among countries, with the most important trend being one of convergence among countries both in terms of publications and citations. Four other general patterns of evolution and positioning were identified by aggregating countries by current scientific status:

- *Group 1: Small sized high income countries (the Scandinavian and Benelux countries) lead in relative impact*: Because of their sizes, these countries have relatively low world shares of publications and citations. Yet, they exhibit excellent relative impact performances measures. For example, the share of cited papers for the Netherlands grew substantially since 1986 and the country is now above the European average in several scientific fields. This growth in the share of papers and citations has been particularly salient in Scandinavian countries as compared to the other European member states, even Benelux countries. Moreover, and despite their small size, the Scandinavian countries are quite diverse in their scientific specialization, with the exception of Denmark. Benelux countries have even broader scientific structures when compared to the Scandinavian.
- *Group 2: European countries represented in the G8 group except Italy (Germany, UK and France) report large shares of publications as well as good impact and visibility in science*. In addition, their impact results are improving in relation to the world base, particularly in Germany. However, these countries are still growing at a slower pace compared with most other member state counterparts and, as a result, still have decreasing growth shares in both paper production and citations (with the exception of Germany in terms of citations). The evenness of quality across scientific fields is another distinctive feature of this group of countries. The UK and France in particular have the most even quality across scientific fields of all EU15. This group also has broad scientific structures, typical of

[21] However, 9 out of these 11 present values are very close to the world base.

mature systems, with a balanced scientific portfolio that enables them to adapt and respond to new and complex scientific requirements. The exception is the UK, which has the most specialized scientific structure of all EU15 countries.

- *Group 3: Southern European countries (Portugal, Spain and Greece) are growing fast, though from a low base*: These countries are characterized by a late international scientific start, with the low volume of papers and citations reflecting this delayed effort. Their investment in research and development is still the lowest of all EU15 countries [23]. As a result, they have low shares of publications and citations but very high growth rates when compared to other European countries. Spain has a better impact performance than Greece and Portugal but its growing at a slower pace in relation to most of the other European countries in this measure. Because of their low resources, all these countries tend to have a rather specialized scientific structure, although they exhibit a rather even scientific quality across scientific fields.
- *Group 4: The in-between countries (Italy, Austria and Ireland) present mixed characteristics* from the previously identified groups. Italy's share of publications and citations is reaching a position close to that of the other G8 countries that are part of group 2. The relative citation impact for the country is also growing at the same rate as group 2 and, much like the other countries in this group, it has a relatively broad scientific system. However, the current scientific impact is similar to the Spanish and the scientific performance in relation to population, labor and GNI is similar to that of the Southern European countries. Austria's scientific system is very similar to the Italian, with the exception that its share of papers and citations is still below the EU15 average. Finally, the Irish system has features that make it very similar to that of other small high income countries, namely in scientific impact, but also to the G8 countries group, including indicators such as scientific performance in relation to population. At the same time it also has one of the most specialized scientific systems in EU15 and its impact growth is similar to that of the countries in the southern European group.

The analysis reveals the different characteristics of the EU15 countries, an aspect already explored in prior science and technology studies [7]. High income countries from group 1 seem to be more efficient than other European countries and their output is of the highest quality and impact. These countries along with the countries of group 2, which have accumulated a huge pool of human resources and knowledge, will be the key players for European Union science in the scientific race between the EU15 and the US for the coming years. It is probable that countries from group 4 will soon attain a similar level of scientific competitiveness as the previously mentioned groups. The Southern European countries of group 3 will take a longer time to consolidate their position within the international scientific community due to their late start. However, their high growth rates indicate that their scientific systems are by no means stagnated. In fact they are closing the gap fast in relation to their European counterparts, though they still have a long way to go.

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