

Global trends in plant transgenic science and technology (1973–2003)

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Transgenic science and technology are fundamental to state-of-the-art plant molecular genetics and GM crop improvement. Monitoring the scale and growth of this area of science is important to scientists, national and international research organizations, funding bodies, policy makers and, because of the GM debate, to society as a whole. Literature statistics covering the past 30 years reveal a dramatic increase in plant transgenic science in Asia during the past decade, a sustained expansion in North America and, recently, a slow down in the rest of the world. With the exception of the output of China and India, publications focusing on the development of transgenic technology have been slowing down, worldwide, since the early mid-1990s, a trend that contrasts with the increase in GM crop-related studies.

Global trends in plant transgenic science and technology

Scientific publications are being used increasingly as an indicator of scientific performance [1–3]; literature statistics, based on published bibliographic records compiled into databases, provide valuable evidence for the overall state of scientific and technological knowledge, particularly in academia [4]. However, such bibliometric studies have been associated with conceptual and operational difficulties [4–8]. A recent bibliometric study, encompassing 30 624 curated bibliographic records up to and including 2003, has led to a re-evaluation of the scale and composition of plant transgenic science literature [9]. This has provided an opportunity to take a fresh look at the growth, scale and evolution of plant transgenic science, according to publication level and citation impact. In conjunction with other indicators (patent awards; funding, employment or business statistics; information from functional genomic databases; non-conventional literature; industry surveys; and information from field trials and commercial culture of GM varieties) literature statistics can help to assess the plant- and agrobiotechnology sectors objectively. In the past, combined analyses of patents and literature have provided valuable information on the interactions between knowledge and technological achievements [10]; furthermore, comparisons between economic indicators and literature have also been used to estimate the scientific impact of national research programmes [1,2]. This review highlights key

trends in plant transgenic science and technology, based on what is known, currently, about the evolution of its associated literature during the past 30 years.

Plant transgenic science and technology publications expanded dramatically in the 1980s following the production of the first transgenic plants using either disarmed binary vectors [11] or direct transfer of DNA [12]. Until 1992 a sustained growth of between 30% and 40% *per annum* led to a near-exponential accumulation of bibliographic records (Figure 1a); since 1992, a regular decrease in annual growth rates (from 28% in 1993 to 12% in 2003) has changed the pattern to a near-linear one. The overall profile of the cumulated literature fits a Gompertz model [13] (Figure 1a) but might also represent the first stages of an exponential growth with saturation in a logistic or S-shape model [5]. This profile is indicative of a dynamic area of science that has passed its initial development phase but has not reached its saturation limit. However, this worldwide picture hides dissimilar trends, depending upon the fields of research, the major economic zones or the countries considered [9].

Trends in plant transgenic science by fields of research

Three areas of plant transgenic science are considered in this review: the development of transgenic technology (DevTech); its non-GM crop applications (AppTech); and its GM crop or feed applications (GMcrop). DevTech represented 15% (4545 records) of scientific publications up to and including 2003, AppTech 71% (21 843 records) and GMcrop 14% (4236 records) (Figure 1a). Trend analysis revealed a dramatic increase in GM crop-related studies during the past decade, a sustained expansion in publication of non-GM crop applications and, since the early to mid 1990s, a slow down in the production of studies focusing on technological development (Figure 1a). In 2003, DevTech publication numbers grew by 8%, AppTech by 11% and GMcrop by 19%. In the same year there were twice as many GMcrop (676) as DevTech (335) studies published worldwide. The increasing reliance of fundamental and applied plant science on transgenic approaches has driven the growth in AppTech and GMcrop. The latter is also fuelled by the increased interest in, and scrutiny of, GM crops and products during the past decade [14,15]. The slow down in DevTech coincided with the last major technological breakthroughs in plant transgenesis, such as *Agrobacterium*-mediated transformation of cereals [16] and the *Arabidopsis* inflorescence-dipping technique [17]. The ratio of DevTech:AppTech:GMcrop publications produced in 2003

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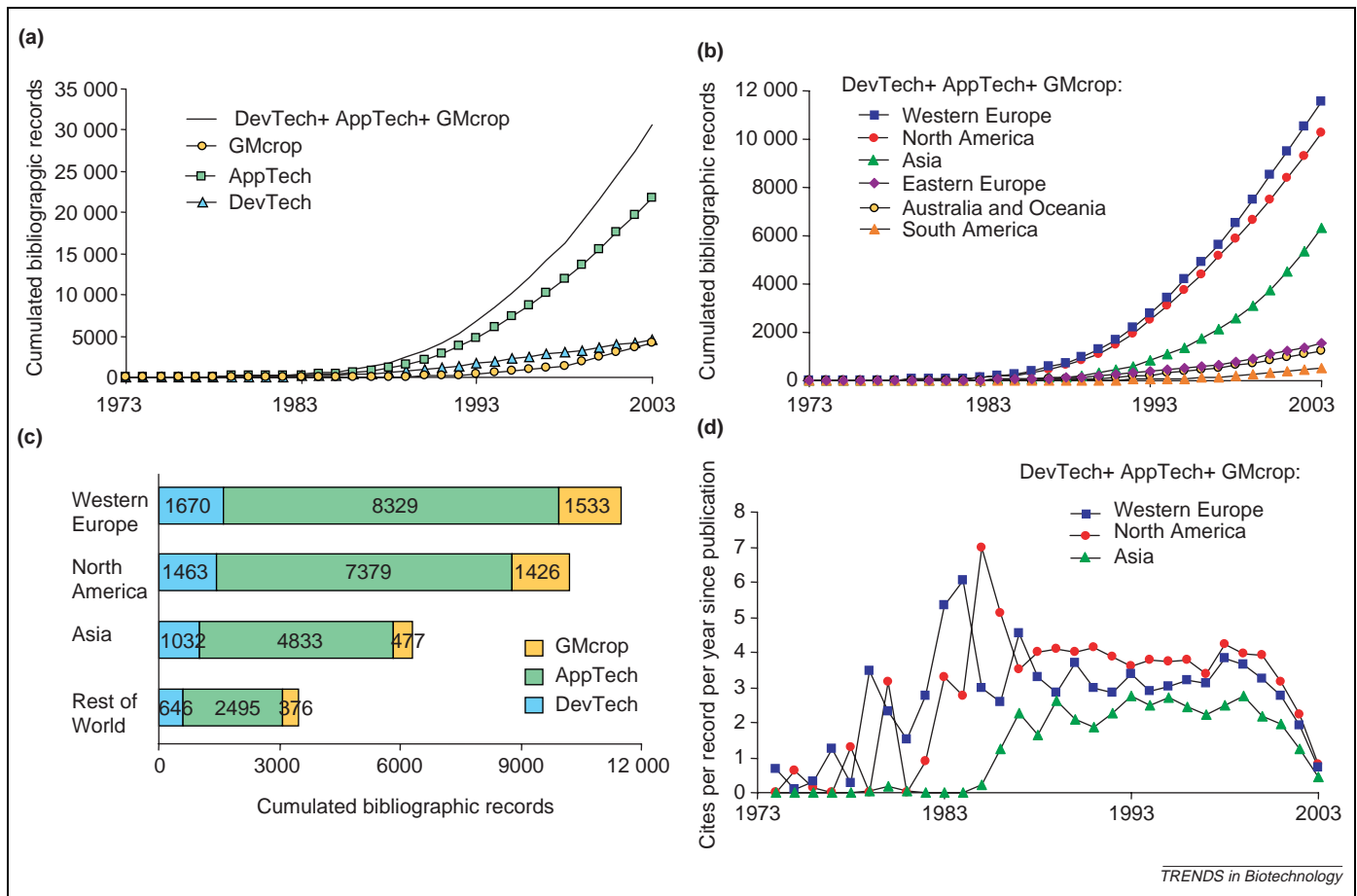


Figure 1. Evolution of plant transgenic science and technology publications in the past 30 years, worldwide and by economic zone. DevTech: studies relative to the development of plant transformation technology; AppTech: studies using plant transformation technology for basic or applied science (except GM crops); GMcrop: studies relative to GM crop and feed. (a) The cumulated production of GMcrop+AppTech+DevTech records (plain line) represents all plant transgenic studies and best fits a Gompertz model: $\alpha e^{-\beta t^\gamma}$ with $\alpha=119500$ (s.e. 5192), $\beta=12.7$ (s.e. 0.2228) and $\gamma=0.9284$ (s.e. 1.470 10–3). Time (t) is given in years, starting in 1973. (b) Evolution, (c) composition and (d) impact of plant transgenic science publications in the past 30 years by economic zone. The impact of each bibliographic record was calculated using the total number of cites in 2004 divided by the age of the record. The number of bibliographic records from Africa was too small to be clearly represented. The list of countries included in each economic zone is detailed in reference [9].

was 1:7:2 compared with 2:7:1 in 1993 and 4:6:0 in 1987. The continued decline in the publication share of technological development will be analyzed in this article, in conjunction with additional geographical and publishing variables.

Trends in plant transgenic science by economic zone

Western Europe (11 532 cumulated records) and North America (10 268 cumulated records) jointly lead this area of science (Figure 1b). During the past 30 years, Western Europe has continuously outperformed North America in terms of cumulated scientific publications. This is in sharp contrast to the dominant position of North America in plant biotechnology patenting [10] and the commercialization of GM crops [15,18], thus confirming the suspected under-exploitation of the European science-base in biotechnology [19]. Furthermore, since 2000 plant transgenic science publication has suffered a slow down in Western Europe [9]. It is noteworthy that the timing of this slow down coincided with the 1999 moratorium on GM crops in the European Union but it might also reflect the general decline of its share of world publications in recent years [2]. Asia occupies third place in terms of total published records (6342), representing around half of the total output of either North America or Western Europe (Figure 1b).

This difference is largely the result of the late start of plant transgenic science in Asia; however, during the past decade, Asia has exhibited faster growth (19% in 2003) than any other region (around 10% in the rest of the world). In 2003, Asia produced the same number of bibliographic records in plant transgenic science (1007) as Western Europe (1034) or North America (978) [9] but only 7.5% of Asian publications focused on GMcrop, compared with 13.6% for the two leading economic zones (Figure 1c). About 50% of the 6342 bibliographic records from Asia were published by the 6342 bibliographic journals. The lack of citation figures for nearly half (43.8%) of the Asian records and their relatively recent publication (Figure 1b) hinders rigorous comparison of impact [6] with the top two economic zones. However, a comparison based on records with associated citation figures suggests a lower impact of Asian studies (1.9 cites per record per year since publication) compared with Western European or North American studies (2.9 and 3.3 cites, respectively). This hierarchy in terms of impact has remained unchanged since 1988 (Figure 1d); before this date, North America and Western Europe alternated as leader. Language bias, where non-English papers remain under-represented or under-cited (if present) in international databases has probably

contributed to reducing both the scale and impact of European and Asian plant transgenic science publications [6,8]. Nevertheless, the dominant position of scientific publications from North America in terms of impact during

the past 16 years suggests a stronger science-base, which has probably contributed to the success of its private plant biotechnology sector. Plant transgenic science publication output from Eastern Europe (1524 records), Australia and

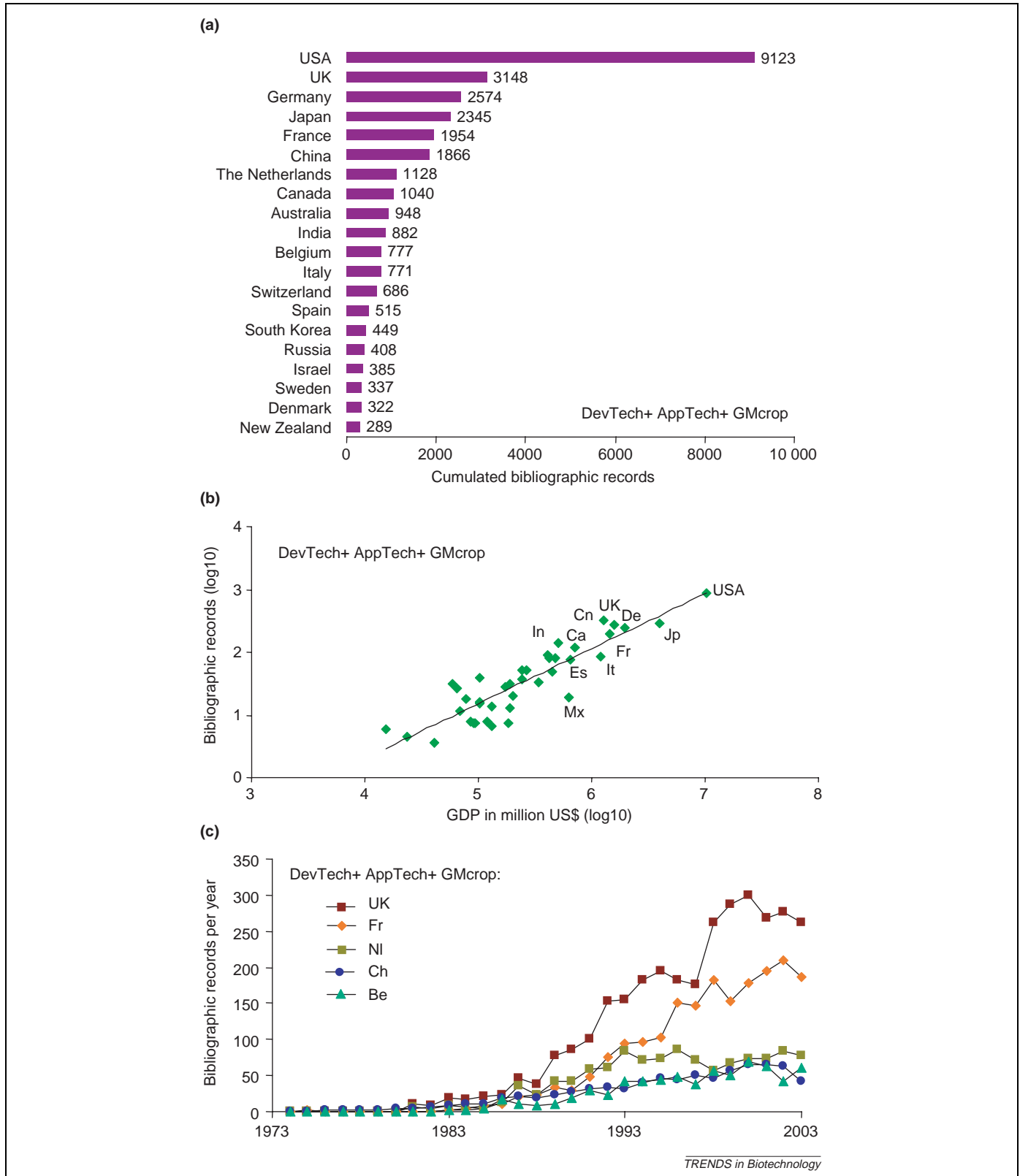


Figure 2. Evolution of plant transgenic science and technology publications (DevTech + AppTech + GMcrop) in the past 30 years by country. **(a)** Scientific publication levels of the top 20 countries. **(b)** Relationship between publication level (average for the period 2002–2003) and GDP (2002; source OECD). **(c)** Annual production of bibliographic records in five Western European countries. USA: United States of America; Jp: Japan; De: Germany; UK: United Kingdom; Fr: France; Cn: China; It: Italy; Ca: Canada; Es: Spain; Mx: Mexico; NI: The Netherlands; Be: Belgium; Ch: Switzerland.

Oceania (1226), South America (535) and Africa (232) were significantly smaller than those from the top three economic zones, and exhibited a similar recent slow down as that experienced in Western Europe [9]. Despite this trend, in 2003 emerging plant transgenic research from South America was above world average with a growth rate of 15%, second only to Asia.

Trends in plant transgenic science by country

The USA is the world leader in all areas of plant transgenic science, with three times as many scientific publications as the UK, and around four to five times more than Germany, Japan, France or China (Figure 2a): to date, the USA has generated 30% of the overall plant transgenic scientific literature. In 2002 and 2003, the leading countries in terms of scientific publication *per capita* were New Zealand, Switzerland, Denmark, Belgium, The Netherlands, Australia, UK, Sweden, Canada, France, USA and Germany, with Japan ranked 18th. During the same period, publication levels relative to GDP *per capita* were highest in China and India, followed by the USA, Brazil, Philippines, Russia, UK, Germany, Japan, France, South Korea, South Africa and Poland. Among the top 40 countries there was a positive and significant correlation ($r=0.79$, $p<0.05$) between the total number of studies published and GDP in the period 2002–2003 (Figure 2b). This indicates that publication levels in plant transgenic science directly reflect the wealth of countries, presumably driven by a higher level of investment in public and/or private research and development [1]. Trends in scientific publication varied widely between countries. In 2003, scientific publication grew by 27.6% in South Korea, 24.3% in China, 22.2% in India and 14.2% in Japan, fuelling the dramatic expansion of plant transgenic science in Asia. In recent years, China and Japan have become second and third, respectively, to the USA in the number of bibliographic records produced every year. Growth in India is probably part of a broader national trend, in which plant science publication generally outperformed the world average during the past decade [20]. In 2003, publication growth rates of 15% in Canada and 10.3% in the USA contributed to a sustained expansion in North America. By contrast, scientific publication levels in most Western European countries, with the exception of Germany and to a lesser extent Italy, remains similar to that of the late 1990s (Figure 2c). Future analyses will determine whether this slow down in Western European countries is a lasting trend.

The case of plant transgenic technology development (DevTech)

The current evolution in plant transgenic science literature has been preceded by a general slow down in the number of scientific publications describing the development of plant transformation technology since the early to mid 1990s. This slow down is noticeable not only in absolute terms but also relative to the entire arena of plant transgenic science (Figure 3a). Since 1985, the relative share of published DevTech studies has decreased continuously from 38.3% (in 1985) to 26% (in 1990) and finally to 10.5% (in 2003). This trend is specific to

technology development because the plant transgenic science literature, as a whole, has continued to expand worldwide during this period (Figure 1a). Only China and India have continued to increase their publication volume in DevTech, resulting in an average growth (China 19%, India 17%) two to three times that of the rest of the world (5–7%) in 2003. In recent years, China and India have become second and third to the USA, respectively, in the number of DevTech records produced every year. This effort in technology development has most probably contributed to the dramatic growth of plant transgenic science as a whole in these two Asian countries. In the USA, Japan, Germany, and to a lesser extent Italy, the stagnation of DevTech publication has had a lesser effect on total transgenic studies than in the rest of the world. Among the top 30 countries, a significant and positive correlation ($r=0.92$, $p<0.05$) can be demonstrated between the total effort in DevTech and the resulting global AppTech plus GMcrop publication level (Figure 3b). All these elements are consistent with the idea that technological development is proportionally influencing plant transgenic science as a whole.

During the past decade, the development of plant transgenic technology has been hampered by insufficient upstream and downstream support, including limited funding, unfavourable market conditions and the tight regulatory framework for GM crops [21–23]. Detailed examination of the literature shows that this phenomenon might have been further amplified by a shrinking base for scientific publication. The slow down in the volume of DevTech publication that occurred worldwide in the mid-1990s was already noticeable five years earlier in journals with an impact factor above one and was slightly more pronounced in journals with an impact factor above two (Figure 3c). The progressive establishment of routine plant transformation technologies and the commercialization of GM crops have probably driven leading plant science journals to concentrate on biological rather than technological plant transgenic issues. Today, only a limited number of, often specialized, journals publish such technological research. The slow down in technology development publications also probably reflects a loss of interest in academia and the sustained technological effort from the private sector, particularly the top six AgBiotech companies from the USA (Monsanto, Dupont, Dow), Germany (Bayer Cropscience, BASF) and UK/Switzerland (Syngenta) [24].

The case of genetically modified crops (GMcrop)

Since 1990, GMcrop literature has grown at around twice the rate of AppTech and DevTech literature (Figure 1a). The share of published GMcrop studies has increased, continuously, from 1.1% (in 1987) to 11.3% (in 1994) and finally to 21.1% (in 2003); however, the GMcrop literature results from various publication practices and is differently represented in the databases. The GMcrop literature includes a large percentage (38.7%) of publications with limited scientific peer review, such as editorial material, news items, books, newsletters and proceedings from meetings, compared with the DevTech (15.8%) or the AppTech (18.4%) literature, which reflects the fact that

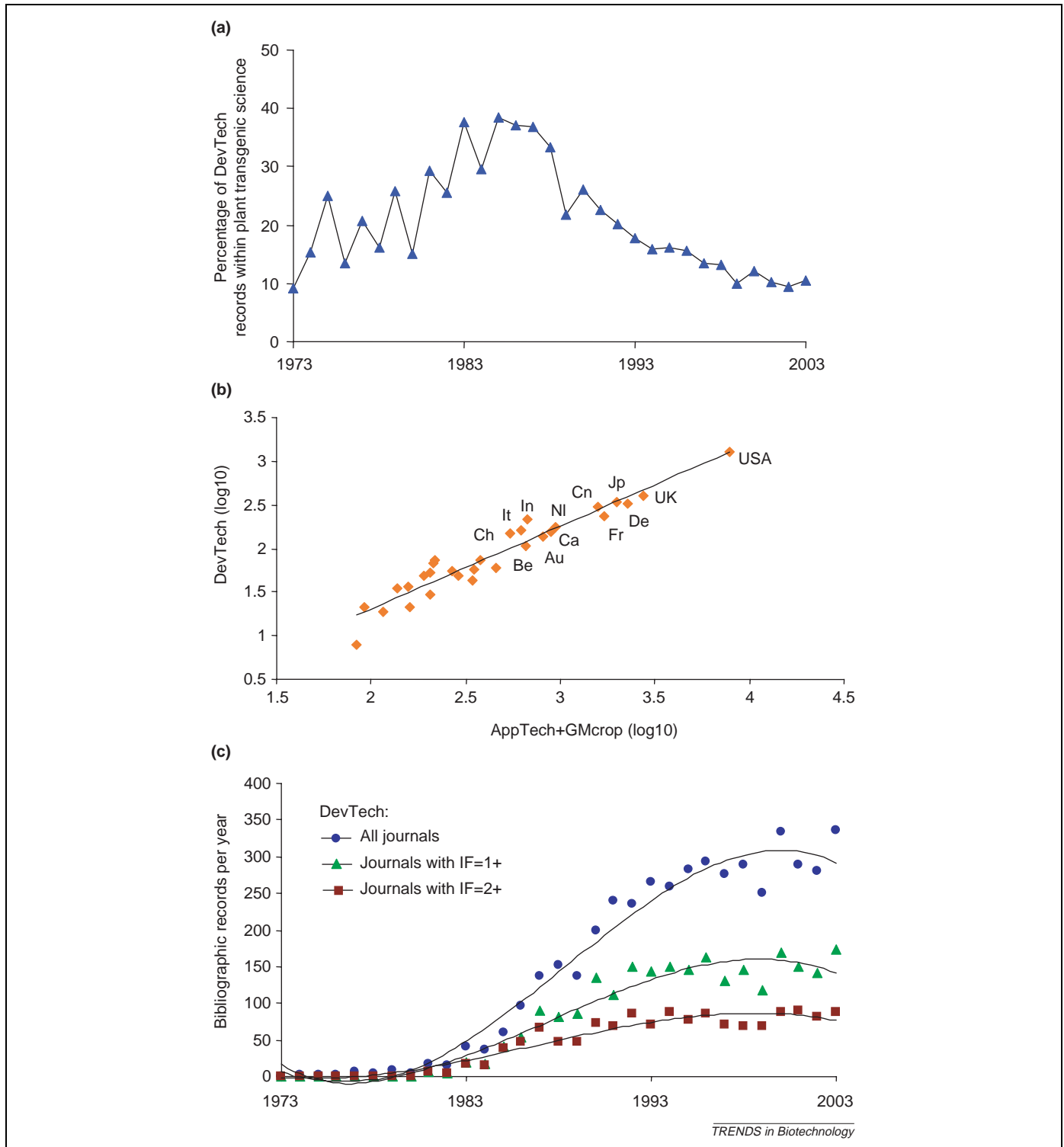


Figure 3. Evolution of plant transgenic technology (DevTech) publications. (a) DevTech share of plant transgenic science publications. (b) Relationship between the development (DevTech) and application (AppTech + GMcrop) of plant transgenic technologies in the top 30 countries (cumulated production for the period 1973–2003). (c) Worldwide evolution of DevTech publications in scientific journals with different impact factors (IF). USA: United States of America; UK: United Kingdom; De: Germany; Jp: Japan; Fr: France; Cn: China; NI: The Netherlands; Ca: Canada; Au: Australia; In: India; Be: Belgium; It: Italy; Ch: Switzerland.

the GM crop debate is often conducted in platforms other than peer-reviewed research articles: the GMcrop literature contains 53.8% scientific journal articles, compared with 73.9% for DevTech + AppTech. These discrepancies in publication practices hinder any global comparison of the impact between these three fields of plant transgenic science [25]. In addition, GMcrop publications are less

represented in some databases, such as ISI-WOS (Philadelphia, USA), than in others, such as CAB Abstracts (OVID Technologies Inc., New York, USA): the former contains around half the number of GMcrop publications, including journal articles and reviews, than the latter. These disparities reiterate the value of assessing world literature across multiple databases [9], as in the present

review. In recent years, China and India, became third and fifth, respectively, to the USA, the UK and Germany in the number of GMcrop publications produced every year.

Conclusion

Plant transgenic publications provide valuable indicators of scientific knowledge and performance in areas central to the plant- and agro-biotechnology sectors [10]. Publication trends during the past 30 years in terms of growth, scale and impact have reflected important changes in plant transgenic science literature, particularly since the 1990s. These include a continued weakening in the publication of technology development (except in some leading Asian countries) and a strong increase in GM crop-related studies. This situation might well erode the science-base needed to improve and evaluate GM crops and products. In the past, transformation technologies have also been seminal to many aspects of plant transgenic science. Key biological discoveries, such as post-transcriptional gene silencing [26] and siRNA [27], emerged directly from the study of transgene behaviour in plants. Technological weakening might, therefore, affect many aspects of plant transgenic science. Since the 1990s, the non-GM crop use of transgenic technology has continued to expand and has remained the primary source of scientific publication in plant transgenic science. At the same time, changes in the share of publications among economic zones have occurred, with Asia reaching annual publication levels on a par with those in Western Europe and North America. Currently, only impact (citations) differentiates the outputs of these three economic zones. Since 2000, the dramatic growth in Asia and the sustained production from North America have prevented a global slow down in worldwide plant transgenic science publication. The faster generation of knowledge in Asia and North America will probably promote more sustainable economic development in domains related to plant science [1,28]; equally, the low research and technology capacity of some developing countries (particularly in Africa) might hamper development.

The future development of plant transgenic science is important to plant science as a whole and still depends on the further understanding, control and improvement of plant transformation technologies. It is equally important that technological knowledge is available and is disseminated, through scientific publications, for the benefit of scientists and policy makers. Technology transfer among nations is essential for capacity building in developing countries [29]. In all these domains, the role of public research is crucial and needs to be reinforced.

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