Mobility, retention and productivity of genomics scientists in the United States

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The United States appears to have an increasingly weakening ability to attract and retain genomics scientists.

Scientific and technological innovations by highly skilled scientists and inventors are critical to the long-term economic health of the United States. These scientists enable the creation and flow of scientific research and technologies from public institutions such as universities to private firms and vice versa by forming vital linkages between them[1]. The exchange of new ideas and the commercialization of promising scientific and technological innovations have resulted in the formation of new high-technology startups[2,3], growth opportunities within entrepreneurial and established science-based firms[4], and jobs creation[5]. These form the backbone of the scientific innovation ecosystem in the United States. A potential brain drain of scientists and inventors from the United States, or a failure to attract them to the United States at previous levels, could challenge its leading role in science and technology, and undermine its long-term economic resilience.

Although bright scientists have been drawn to the United States by its world-class universities, dynamic companies, availability of funding and free socioeconomic environments for scientific research, anecdotal evidence from space exploration[6], high-energy physics[7] and biotech[8] increasingly point to the possibility that the United States might no longer be able to retain or attract these scientific researchers and inventors at previous levels. A Kauffman Foundation–funded survey[9] suggests that, increasingly, the United States is less able to retain and attract new scientific talent, as more scientists are returning to emerging economies such as Brazil, Russia, India and China (BRIC) and, to a lesser extent, to other non-US Organisation of Economic Cooperation and Development (OECD) countries.

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Apart from such anecdotal evidence, there has been little or no large-scale systematic examination of the degree of a possible decline in scientific talent retention and attraction to the United States compared with the rest of the world, and how the productivity of scientists in the United States has changed over time.

In the following article, we address these important questions by providing the first detailed longitudinal assessment of the mobility, retention and productivity of scientists in a specific field of biology in the United States relative to the rest of the world, particularly the non-US OECD and BRIC countries. The field we chose as our focus is genomics as it has been an integral part of biotech and genomics innovation[10] since the Human Genome Project—a 13-year, \$3.8-billion research effort, which was one of the largest science projects ever funded by the US Department of Energy and the US National Institutes of Health. Furthermore, many genomics innovations covered by patents have demonstrated a high level of novelty and utility and form the major sources of downstream revenue for healthcare, biotech and pharmaceutical companies[11].

Study design and methodology

We studied the entire population of 5,809 scientists who have contributed to innovation in genomics and undertook the first step to commercialization by having at least one granted genomics patent by 2005. Following prior research[12], the definition of a genomics patent granted by the United States Patent and Trademark Office (USPTO) is highly specific in its identification of patents that actually claim human nucleotide sequences. The sampling approach based on inventors with at least one granted patent is also consistent with previous studies[13]. We constructed and traced the detailed location and mobility patterns of each of these scientists across the world through their organizational affiliation each year over a 22-year period from 1988—the publication year of the first matching genomics paper to the genomics patent[14]—until 2009. 1988 is also the landmark year when the first concerted genome research program was started, as recommended by the US Congressional Office of Technology Assessment and US National Academy of Sciences National Research Council committees.

The location for each scientist is captured from scientific publications collected from the ISI Web of Science (Thomson) database (which offers one of the most comprehensive coverage of peer-reviewed scientific research articles and the addresses of the scientists). To identify and track their location, we first downloaded all the publications for all of the scientists in our sample. Then, in any given year, as long as they had at least one publication in that year, scientists were assigned to the organization address that was listed as their affiliation on the cover page of the publication. This was done automatically for cases where Web of Science provided precise tagging of an address to a scientist and it was done manually (i.e., by visual inspection of the cover page of the actual article) whenever this was not the case. This information is supplemented with scientists' curriculum vitae or online career profiles from official university or firm websites, where applicable. (Further details of the data set construction are available upon request.)

The scientists in our data set produced a total of 37,647 unique patents and 264,531 unique publications from 1988 to 2009; an average of 6.48 patents and 49.54 publications per scientist within this period. About 80% of the scientist-year observations captured a

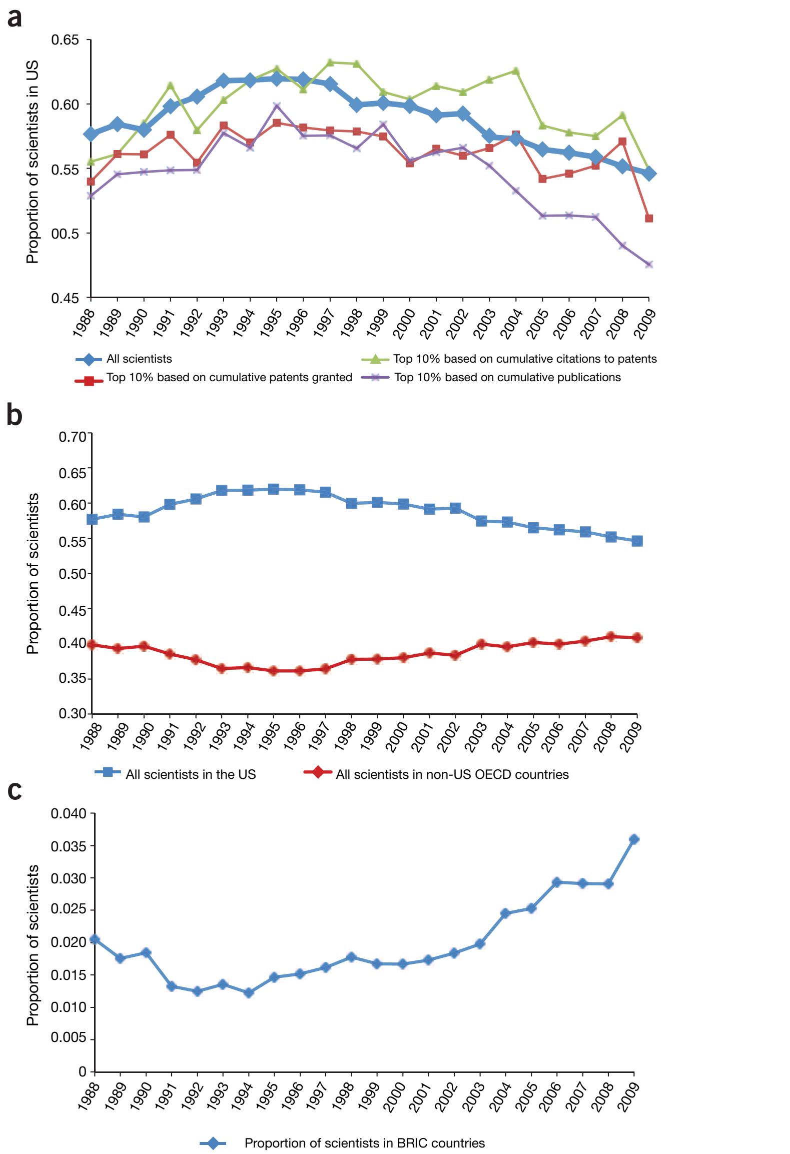

Figure 1 Proportion of scientists in different countries. (**a**) Proportion of scientists in the United States. (**b**) Proportion of scientists in the United States and non-US OECD countries. The non-US OECD countries in our sample are: Australia, Austria, Belgium, Canada, Chile, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, Korea, Mexico, the Netherlands, New Zealand, Norway, Poland, Slovak Republic, Spain, Sweden, Switzerland and the United Kingdom. (**c**) Proportion of scientists in the BRIC countries.

public sector address, which includes universities, university hospitals and other public research institutes, whereas the remaining 20% captured a private sector address of a firm.

Proportion and number of genomics scientists

Out first question was, is the United States losing scientists to other countries? Because the "entry" of genomics scientists into our sample is defined by either the first genomics patent application or paper publication, we report the results of our analyses from 1988 onward. We found that there was an initial increase of 7.3% in the proportion of all genomics scientists residing in the United States, from 0.58 in 1988 to 0.62 in 1996. However, this was followed by a decrease of 11.8% to fewer than 0.55 in 2009 (**Fig. 1a**). The trajectories were similar for "star" scientists—the top 10% of the scientists in our sample based on either cumulative patents granted or cumulative citations to patents. The top 10% of the scientists based on cumulative scientific publications experienced an even sharper decrease (17%), from 0.58 in 1996 to less than 0.48 in 2009. Further investigation shows that this pattern of overall decrease was similar among more or less experienced scientists, based on their year of first patent application or scientific publication.

This contrasts with the situation in the non-US OECD countries where the proportion of genomics scientists first decreased by 9%, from almost 0.40 in 1988 to 0.36 in 1996, but increased by more than 13% to about 0.41 in 2009 (**Fig. 1b**). Similarly, for the BRIC countries, the proportion of genomics scientists first decreased from 0.020 in 1988 to 0.015 in 1996, but increased by 137% to 0.036 in 2009 (**Fig. 1c**). In particular, the proportions of genomics scientists in China and India from 1996–2009 grew by 165% and 85%, respectively.

Furthermore, the average amount of time these scientists spent residing in the United States (holding either permanent or temporary positions) over the previous 3, 5 and 7 years fell by 13%, 11.6% and 8.4%, respectively, from 1996 to 2009. In contrast to this pattern, the average amount of time these scientists spent at positions in non-US OECD countries increased by 14.7%, 12.5% and 7.8% between 1996 and 2009 for the previous 3, 5 and 7 years, respectively. Likewise, BRIC countries experienced an increased presence of these scientists, as evidenced by the 121%, 102% and 74% increases between 1996 and 2009 for the previous 3, 5 and 7 years, respectively (details available upon request). To the extent that geographic proximity of scientists facilitates greater transfer and spillover of (both codified and especially tacit) knowledge and knowledge recombination to produce innovations[15–18], a reduction in the attraction and retention of genomics scientists in the United States may have undesirable consequences regarding knowledge creation, sharing and innovative activities in the United States, compared with earlier times where the presence of such scientists in the United States was higher.

Do the losses differ between the public and private sectors? Further investigation revealed that the declining trend in the proportion of all genomics scientists residing in the United States since the mid-1990s has been driven primarily by the reduction of scientists from the public sector—universities, university hospitals and public research institutes. The proportion of all genomics scientists in the public sector who resided in the United States was 0.58 in 1996 but dropped by 13.1% to fewer than 0.51 in 2009 (**Fig. 2a**). On the other hand, the proportion of all scientists affiliated with private sector firms who resided in the United States first experienced an increase from 0.68 in 1988 to 0.74 in 1996 and remained relatively stable until 2009 at 0.74 (**Fig. 2a**). The scientists who belonged to the top 10% based on cumulative patents granted, cumulative citations to patents or cumulative scientific publications showed similar trends for the public and private sectors. Likewise, this same pattern held for subsamples of more, or less, experienced scientists.

Comparing these trends in the United States with the situation in the non-US OECD countries (**Fig. 2b**), we found the opposite pattern. The proportion of all scientists in the public sector who resided in non-US OECD countries increased steadily from 0.39 in 1996 by more than 12.4% to 0.44 in 2009. On the other hand, the proportion of all scientists in the private sector who resided in non-US OECD countries decreased by about 2% from 0.26 in 1996 to 0.25 in 2009. Similarly, most of the increase in the BRIC countries came from scientists who were in the public sector. The proportion of scientists in the public sector in BRIC countries increased by 121%, from 0.019 in 1996 to 0.043 in 2009.

The changes in the absolute number of scientists in our sample over time are consistent with the trends indicated by the proportions we report. Because **Figure 2a** shows that the decrease in the United States was driven largely by public scientists, we focus here on public scientists. (Other figures on the absolute number of scientists are available upon request.) **Figure 3** depicts the absolute number of scientists in the United States and in non-US OECD countries who were in the public sector. The drop in the absolute number of scientists in the public sector was much steeper in the United States than in non-US OECD countries. Taking the years 1996 and 2005, the 2005 figure for the United States was only 81% of what it was in 1996 (i.e., the number of scientists was 1,249 in 2005 and 1,543 in 1996). In contrast, in non-US, OECD countries, the 2005 figure was 99% of what it was in 1996 (i.e., the number of scientists was 1,027 in 2005 and 1,038 in 1996).

Furthermore, analyzing the subsample of scientists for whom we had an address in every year produced a consistent pattern with that displayed in **Figure 3**. We found a decreasing trend since the mid-1990s in the number of scientists in the public sector who were in the United States whereas the opposite trend was observed for non-US OECD countries. If we use this same sub-sample to consider the overall number of scientists, regardless of sector, over time for the United States and non-US OECD countries, we again see a consistent pattern.

Productivity trends

What are the scientific and innovative productivity trends of these genomics scientists? We measured the scientific productivity of a researcher as the average number of scientific papers published per individual in a particular year (t). A genomics scientist in the United States produced an average of 1.27 scientific articles in 1988. This increased to about 1.83 in 1996 but decreased to less than 1.70 in 2009. On the other hand, productivity for scientists who were not in the United States climbed substantially from 1.51 in 1988 to 2.57 in 2009, representing an increase of 71%. The average scientific productivity of genomics scientists not residing in the United States was consistently higher than those in the United States. The difference was small until 1996 but grew through 2009. Using an alternative data set of genomics publications—scientific articles authored by genomics scientists in our sample published between 1988 and 2009 where a genomics-related keyword[19] appeared in either the title or the abstract of the publication—we obtained similar and consistent results (available upon request).

Scientific productivity in the public sector in the United States was consistently higher than that in the private sector in the United States, although the difference has remained small. Although the strong showing of the private sector might appear surprising at first, it could reflect the tendencies of many genomics companies, especially the disproportionate number of small and medium ones, in the period of our study, to engage in open science (through scientific publications) to both attract the best scientific talent and provide potential investors with validation of their platforms. This willingness to publish contrasts with the behavior of larger corporations, such as big biotech and pharmas, which were more likely to discourage open science and which prefer trade secrets.

Although the productivity of scientists in the public sector outside the United States was also higher than that of scientists in the private sector outside the United States, the gap widened from the mid-1990s to 2009. This suggests a relative increase in productivity in terms of scientific publications for scientists in the public sector outside the United States compared with that of the scientists in the country over the past two decades. Analyses using only genomics publications yielded similar and consistent results (available upon request).

Figure 4 shows the innovative productivity

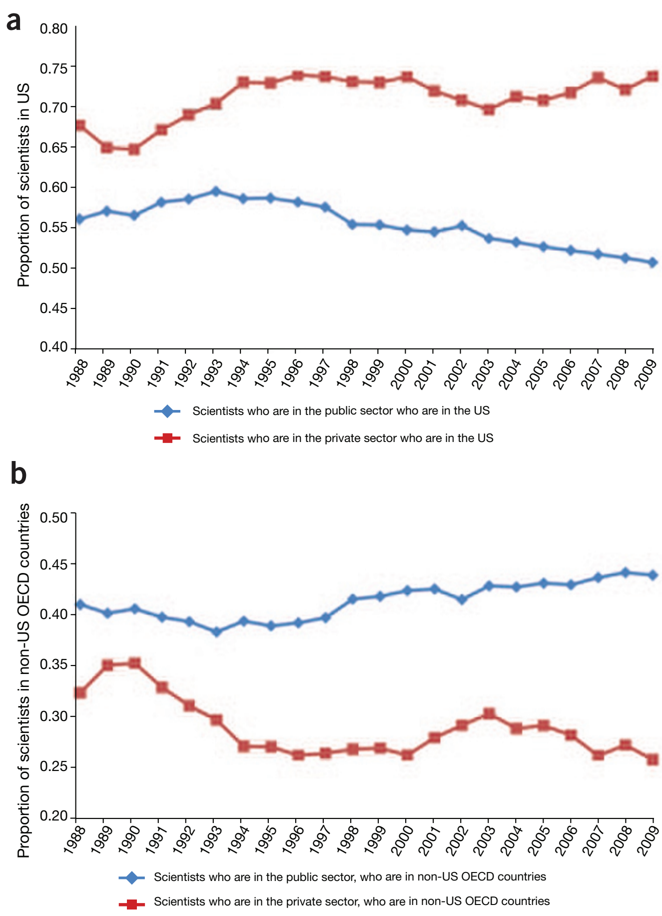

Figure 2 Trends in genomic scientists in the public and private sectors from 1988 to 2009. (**a**) Proportion of scientists in the United States, broken down by public and private sector. (**b**) Proportion of scientists in non-US OECD countries, broken down by public and private sector.

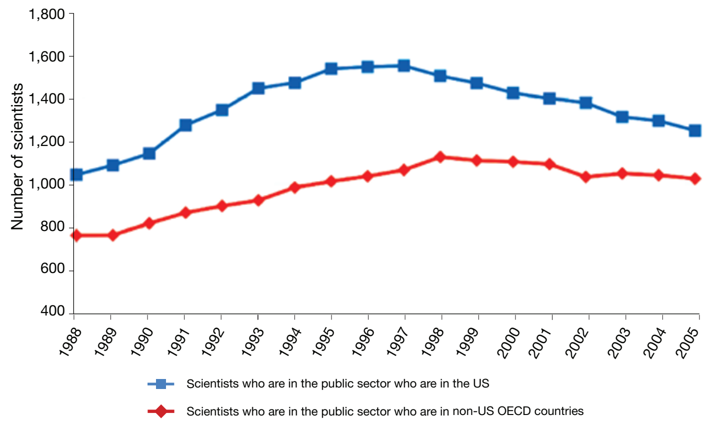

Figure 3 Number of scientists who are in the public sector who are in the United States and non-US OECD countries.

of the scientists measured as the mean number of patents awarded three years into the future ($t + 3$) for each scientist in a particular year (t). Therefore, we computed the average innovative productivity for each scientist from 1988 to 2006. We report $t + 3$ years because it takes on average about 3.3 years between the application and grant of a genomics patent[14]. We replicated our analyses using alternative cut-offs such as t, $t + 2$ and $t + 4$ and the patterns depicted in **Figure 4** remain consistent.

It should be noted that the sharp increase in the average number of patents granted to US private firms in 2003 and 2004 was likely due to the major changes in patent law as stipulated by the American Inventors Protection Act of 1999 (AIPA). The publication provisions of AIPA and the corresponding new rules provide for mandatory publication of all new nonprovisional utility patent applications filed on or after November 29, 2000. Under the new rule, a patent application has to be published at around 18 months from the earliest priority date claimed. To avoid such mandatory disclosure, a substantial increase in the number of genomics-related patent applications by firms took place in 2000. As these applications take about 3 to 4 years on the average to be granted, one sees the uptick in granted patents in 2003 and 2004. Another factor that might have contributed to this increase is that the patent claims granted by the USPTO in specific classes may have become narrower or more stringent over the years, especially since the early 2000s, on what is patentable matter and utility. These changes might have prompted more patent filings for full genes, cDNAs and expressed sequence tags, which likely accounted for the increase in patents granted in 2003 and 2004, once the USPTO cleared the backlog.

As expected, **Figure 4** shows that scientists in the private sector firms in the United States consistently produced more genomics inventions than those in universities and public research institutes in the United States. Similarly, scientists in the private sector outside the United States had higher innovative productivity than those in the public sector outside the United States. Moreover, further analysis suggests that the difference in the innovative productivity of scientists between private and public sectors in the United States increased substantially over from 1988 to 2005 whereas that difference for scientists outside the United States decreased slightly. Scientists in the private sector firms in the United States gained substantially in innovative productivity compared with their counterparts in non-US firms. This might reflect the faster expansion of the US biotech industry, and in particular, US genomics companies, than the expansion of enterprises in other countries over the same period[20]. On the contrary, scientists in universities and public research institutes in the United States did not gain much against their counterparts in non-US public institutions.

We also conducted additional analysis to check whether any of the decline in the number of US genomics scientists and innovative productivity we observed was simply due to the obsolescence of certain areas in genomics technology, which might reduce the likelihood of patenting in these areas or reduce the subsequent impact of these patents. To do this, we identified and constructed a data set of patents based on a group of 29 six-digit 'cutting edge' USPTO patent classes—including proteomics, metabolomics, epigenetics, synthetic biology and molecular engineering—and another group of 109 'non-cutting-edge' classes, both within the areas the genomics scientists in our sample worked on (details of the identification and construction of the data set are available upon request). We then compared the number of patented inventions (as a proxy for inventive activity) and citations to patents (as a proxy for impact) in these two different groups of classes.

Our analysis shows that the temporal patterns of innovative activity in cutting-edge and non-cutting-edge classes (within the research areas engaged in by the genomics scientists in our sample) were similar—in terms of either the production or the impact of these patented inventions (details available upon request). This suggests that even though there might be other differences between the cutting-edge and non-cutting-edge areas within the broader field of research we consider, it seems that genomics intellectual property even in non-cutting-edge areas of industrial application continued to garner a level of activity, attention and impact that was close to the work in the cutting-edge areas. Therefore, to the extent that the presence of scientists in this field in the United States was lower than before, and geographic proximity is beneficial in the recombination and transfer of knowledge and the production of innovations,

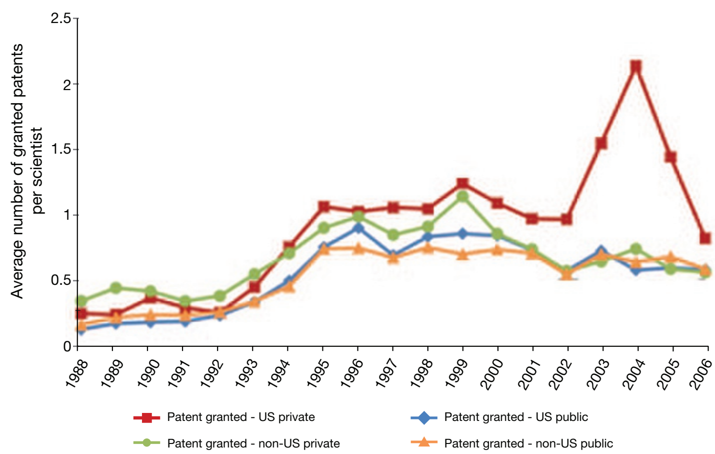

Figure 4 Patents granted to scientists, broken down by US/non-US and by private/public sector.

the changes in the patterns of the location of the scientists in our sample might still have had an impact on the change of patenting activity and on important research within this area.

Analyzing innovative productivity

As the focus of this study was the innovative productivity of genomics scientists who contributed to innovation by having at least one genomics patent, we report results from scientist-level regression models using the number of patents granted to a scientist three years from the current year as the dependent variable. We estimated scientist fixed-effects negative binomial regressions (all regression results available upon request). The predicted values calculated from the results show that between 1991 and 2006, for example, the productivity of scientists on average (in terms of granted patents) increased. Similar results were obtained if we used other comparable early and late cut-off years. Depending on whether the scientist was in the public or private sector and in or outside of the United States, this increase ranged from an average of 0.67 to 1.25 patents granted per scientist. (Using the baseline figures for 1991, these increases in average productivity correspond to at least a 200% increase.) Given the increased interest and wider applications of genomics innovations and the availability of additional resources between 1991 and 2006, such higher productivity is not surprising. However, in light of the decreasing proportion of scientists in the public sector who were in the United States, and the relatively steady proportion of scientists in the private sector who were also located there (**Fig. 2a**), we wished to further explore the possible changes in productivity among private/public and in the US/non-US sets of scientists.

With regard to the increased innovative productivity from 1991 to 2006, we found that there was a 94% advantage for a scientist to be in the private sector in the United States (compared with being located in the rest of the world) over being in the public sector in the United States (compared with being located in the rest of the world). To clarify this: a scientist located in the United States from 1991 to 2006 increased their productivity more than a scientist located anywhere else in the world, regardless of whether that scientist was in the public or private sector. This increase in productivity, however, was 94% higher for scientists in the private sector than for those in the public sector. On the other hand, scientists in the public sector who were not in the United States (of which 98.7% were in either non-US OECD countries or the BRIC countries) had relatively higher growth in their productivity than those in the private sector.

Together with what our figures depict regarding the decreasing proportion of scientists in the United States (**Fig. 1a**), and in the public sector in particular (**Fig. 2a**), this suggests that, over time, the more productive scientists in the United States might prefer the US private sector to the public one, or more productive scientists in the public sector might increasingly prefer to remain in, move back to, or spend more time in non-US OECD or the BRIC countries. These preferences might be tied to changes in the availability of public research funding or other opportunities. Our aim in this study was to establish the pattern with the hope that further studies could investigate in detail the factors responsible for this pattern.

Limitations and future research directions

Our study has some limitations that present potentially fruitful avenues for future research. First, although the number of patents is a reasonably good surrogate to analyze and compare innovative productivity over time, it is an imperfect measure. For example, the patent claims granted by the USPTO in specific classes may have become narrower or more stringent over the years, especially since the early 2000s, on what is patentable matter and utility. These changes might have prompted more patent filings for full genes, cDNAs and expressed sequence tags, which likely accounted for the increase in patents granted in 2003 and 2004 once the USPTO cleared the backlog. Second, although we consider scientists who have contributed to genomics innovation by having at least one granted genomics patent as suggested by previous research[13], several biotech patents might claim human nucleotide sequences but do not in fact directly involve genomics technology. This may have resulted in a few cases of the inclusion of scientists in our sample who might in fact not work directly on genomics technology. Third, our study focuses on the creation of knowledge and patented inventions as a necessary first step in the path leading to successful commercialization. Although it is important to study the creation of inventions and to understand the location of scientists who created these inventions, we acknowledge that the ability to exploit value is separate from the ability to invent and patent. For example, inventions patented in the United States might not be exploited in the time period we study, or they could be exploited by firms from outside the United States or vice versa. Fourth, the successful commercialization of these inventions might be associated with other factors such as the availability of and access to risk capital; this could be another interesting future research direction in how such access varies across time and geography.

Conclusions

Three salient findings stand out from our study. First, the proportion and number of genomics scientists and the amount of time they spent residing in the United States decreased from the mid-1990s to 2009. This contrasts with the increase in the non-US OECD countries and BRIC countries, particularly in China and India. This could suggest an important change in the ability of the United States to attract and retain genomics scientists at previous levels. Second, the loss was driven largely by public sector scientists in the United States, and public sector scientists accounted for ~80% of all scientist-year observations in our study. On the other hand, public sector scientists made up most of the gain in non-US OECD and the BRIC countries. This could point to a potential long-term erosion of the US university-industry linkage and a weakening of its innovation ecosystem. Third, although the innovative productivity of these scientists in both private and public sectors in the United States increased over two decades, the growth in the public sector slowed down relative to the public sector in non-US OECD and BRIC countries. This may suggest a gradual reduction in the competitive advantage of scientists in the public sector in the US in generating biotech innovations.

A possible reason for the gradual reduction in the proportion and number of public scientists in the United States could stem from issues with the availability of federal funding[5]. Nevertheless, although the increase (and decrease) in the proportion and number of genomics scientists in the United States, particularly in the public sector, correlate with the growth (and decline) of federal funding in genomics, such as that administered through the Human Genome Project[21], establishing a conclusive causal linkage was beyond the scope of this study.

Future studies could investigate the causal relationship between government funding (or the number of sponsoring organizations in the public or private sector), scientific mobility and innovative productivity. In particular, funding and patents appear to go hand in hand[22,23], and future work could investigate how temporal and geographic variation in funding might explain part of the variation in productivity. Focusing on genomics scientists has allowed us to examine comprehensively the temporal and spatial trajectory of their mobility and retention, and their productivity in terms of patents and publications. To the extent that scientists in general are driven largely by incentives to publish (and, increasingly, to patent) and are affected by external research and infrastructure support, our findings could potentially be generalized to other biotech fields. Nevertheless, future studies could use a similar approach to study other fields to see whether there are differences in the trends we have documented.

Lasting economic growth emerges from the most advanced science and technology[24]. Scientists and inventors play a pivotal role in shaping America's innovation system. Findings from this study illustrate an apparent weakening of the ability of the United States to attract and retain genomics scientists at previous levels. This could be of concern to policymakers and other key stakeholders. Relevant government and funding agencies should be aware of these ongoing trends and might have to rethink immigration policy, make available more federal funding for major scientific research initiatives, which are both basic and applied in nature[25], and continue reinforcing the US innovation ecosystems and scientific entrepreneurship in the face of increasing global competition. Such major steps might be necessary to reverse the trajectory we document by retaining and attracting the best and brightest scientific talent.

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COMPETING FINANCIAL INTERESTS

The authors declare no competing financial interests.

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