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Research Workforce Diversity: The Case of Balancing National versus International Postdocs in US Biomedical Research

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Abstract

The US government has been increasingly supporting postdoctoral training in biomedical sciences to develop the domestic research workforce. However, current trends suggest that mostly international researchers benefit from the funding, many of whom might leave the USA after training. In this paper, we describe a model used to analyse the flow of national versus international researchers into and out of postdoctoral training. We calibrate our model in the case of the USA and successfully replicate the data. We use the model to conduct simulation-based analyses of effects of different policies on the diversity of postdoctoral researchers. Our model shows that capping the duration of postdoctoral careers, a policy proposed previously, favours international postdoctoral researchers. The analysis suggests that the leverage point to help the growth of domestic research workforce is in the pregraduate education area, and many policies implemented at the postgraduate level have minimal or unintended effects on diversity.

Keywords

research workforce development; diversity; biomedical science; postdoctoral researchers; National Institutes of Health

INTRODUCTION

Maintaining a robust science workforce is increasingly important for continued economic growth. In the USA, funding for postdoctoral researchers [postdocs (PDs)] is a major tool in the arsenal of federal agencies such as the National Institutes of Health (NIH) and National Science Foundation, which continue to provide considerable funding support for the research enterprise, specifically with the goal of increasing the supply of new researchers. Data show that especially in biomedical sciences, postdoctoral training has become a common practice for PhD graduates (FASEB, 2012). Over a 30-year period between 1978 and 2008, the number of PD in biomedical fields in the USA has more than tripled from around 11 000 to more than 35000 (FASEB, 2012).

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The availability of funding for postdoc positions from multiple sources has made them attractive temporary research jobs and consequently has also attracted more international PhDs. In 1979, 73 per cent of biomedical PDs were US citizens, but this number dropped to 48 per cent in 2008. Although international PDs can involve in domestic research activities and foster innovations in science (Chellaraj *et al*., 2005; Stephan & Levin, 2001), there are no guarantees that after training they will stay in the USA. As overseas research opportunities change, many international scholars might leave for opportunities in their home country, which might adversely affect the availability of highly trained researchers working in the USA.

Concerns about the citizenship of scientists are also related to the long-run shifts in research funding and discovery away from the traditional locations in the USA and Europe and towards Asia. Recently, countries such as China and South Korea have substantially increased their funding for scientific research in comparison with the USA (Science and Engineering Indicators, 2012). In the competitive and global market, countries that maintain a high-quality research workforce can benefit from innovative and high technology products.

Furthermore, the declining proportion of domestic researchers raises concerns about adequacy of the workforce in many security–sensitive domains that demand only domestic workforce. Many US companies have recently expressed their concerns about the shortage of domestic science, technology, engineering and math (STEM) workforce. As a reaction, they try to keep their experienced experts and encourage them to postpone their retirement age (Stinebaker, 2012). Therefore, it is reasonable for any government to carefully monitor and examine workforce trends, particularly in regard to the citizenship of researchers.

In this paper, we report on a study designed to understand the dynamics of change in the number of national and international PDs in biomedical sciences over time and to explore the consequences of changes in funding and other policy options. The primary purpose of the research reported here is to address a question raised by our stakeholder, NIH, on the effects of capping the duration of funding for PDs on the diversity of the postdoc population. Our analysis is directed toward understanding the national and international flows into and out of postdoc careers and modelling the dynamics of change in the number of PDs over time. The model will be used to conduct simulation-based analyses of effects of different policies.

POSTDOCTORAL POSITIONS: FLOWS, STOCKS AND TRENDS

Postdoc Population

Postdocs are broadly defined as individuals that hold a doctoral degree and work in a *temporary* research role. University-based research laboratories are the primary employers of PDs. PDs are often distinguished from technicians, graduate students or research scientists, but might work in research teams with these individuals. The purpose of a postdoctoral position is to '…acquir[e] the professional skills needed to pursue a career path of his or her choosing' (National Postdoctoral Association, 2012). Based on this definition, a postdoctoral position is a training and professional development stage in one's career.

Researchers flow into the pool of PD positions mainly from PhD programmes and flow out of PD positions into the pool of permanent positions including tenure-track academic jobs or jobs in industry. The flows in and out of PD positions cross geographical boundaries, where PhD graduates can enter from other countries, and can exit to international jobs after a period of postdoctoral training.

Although there is evidence for positive effects of postdoctoral training on research workforce development (Gentile *et al*., 1989; Levey *et al*., 1988; Steiner *et al*., 2002; Su, 2011), the training also works as the nation's buffer (stock) of STEM workforce, especially for researchers that do not find a permanent academic position (Zumeta, 1984, 1985) or have visa restrictions (Lan, 2012). Therefore, PDs can be hired when needed and let go when they are not. Unlike faculty research hires that earn tenure and lifetime employment, PDs are by definition flexible labour. This tradeoff between PDs and faculty is an example of how the internal labour market in the university has responded to market forces and structural shifts in employment in recent decades (Osterman, 2000; 2011; Osterman & Burton, 2004).

In addition, postdoctoral training is a gateway to the research enterprise, and many research fields use postdoctoral opportunities as a key starting point for the careers of new scholars. Through these opportunities, young scholars learn to direct groups of research students, write grant proposals and improve their own knowledge of the field. These postdoc opportunities have been increasingly attracting young scholars. They are also attractive to the employers because they are relatively inexpensive, compared with tenure-track academics with similar backgrounds and training.

Competing Explanations for Postdoctoral Trends

Figure 1 shows the trends of biomedical PDs in US institutions for both national and international scholars over the past 25 years. International PDs include PDs that are temporary residents (visa holders) who might have got their PhD degree from US or non-US institutions. The number of total PD has increased, while the growth in the number of international PDs has been faster than for national PDs. The number of international PDs in this period has increased by about 400 per cent.

There are several possible explanations for these trends. In the stock–flow metaphor (Sterman, 2000) of PDs, the number of PDs should increase if the inflow of researchers into postdoc positions is more than the outflow. Data show that the inflow is more than the outflow, and there is even an increasing trend in the inflow of researchers to postdoc positions with a relatively constant or declining outflow to faculty positions. In 1985, the number of PhD graduates fromUS universities in biomedical fields was 4160 (501 of them were international), and in 2010, the number increased to 9069 (2331 international). A higher supply of PhD graduates, a portion of whom cannot find tenure-track positions but are still interested in academia, enter postdoc positions. On the outflow side, with an exception of computer science, the number of tenure-track faculty positions in academia has been relatively constant in most major fields in the past 20 years (National Science Foundation, 2012). Other factors such as the removal of a mandatory retirement age in academic positions in 1995 have resulted in even fewer vacancies in academiainthe USA, as current senior faculty stay for a longer period in academia (Larson and Gomez, 2012). A higher inflow of PhD graduates in comparison with the hiring rate in tenure-track positions in academia results in accumulation of PhD graduates who do not find academic positions; some of whom choose postdoctoral jobs.

In addition, the increase in funding opportunities has resulted in a higher demand and a higher capacity for postdoc positions. The increase in NIH research grants, especially in 1998–2003 during which NIH funding doubled, has provided more opportunities for research centres to fund PhD students and hire PDs (Teitelbaum, 2008; Gomez Diaz *et al*., 2012; Larson *et al*., 2012). More funding has also attracted international researchers with PhD degrees from inside and outside the USA (Teitelbaum, 2008).

Flows of Citizens and Non-Citizens into Postdoc Careers

The citizenship of postdoctoral recipients has remained a public policy issue. In a recent study, Wei *et al*. (2012) reported that over 50 per cent of PDs were temporary visa holders. Although there are significant differences across institutions in the percentage of PDs from other countries (which ranges from 34 per cent to 78 per cent), overall PDs from other countries are playing a critical role in many labs. As Cantwell & Lee (2010) report, just what constitutes an international postdoctoral worker in this modern economy is difficult to determine. However, there is a broad acceptance that individuals who are not citizens or permanent residents of the nation—but are working there— can be considered international workers.

Bound *et al*. (2009) analysed the number of doctoral degrees awarded in science and technology and showed that there is an increasing trend in the number of international doctoral students in the USA. They offered several explanations, including the rise in the bachelor level education in the home countries of the international students, as well as the expansion of federal funds for science and technology education in the USA.

As stated, from a policymaker's standpoint, the fact that a portion of international scholars might leave the USA after training raises a wide range of concerns about the long term effects of spending government funds on training international researchers. Unfulfilled demand for domestic research workforce in high-tech and security-sensitive projects is also a policy concern. The newly passed legislation by the United State House of Representatives (2012), also known as the *STEM Jobs Act*, which will offer an additional 55 000 green cards to the most highly qualified foreign graduates of American universities in STEM fields is an indicator of the government level concern to keep high quality international STEM workforce in the country.

This paper aims at providing a framework for investigating the dynamic trends of national versus international scholars and thus developing a policy tool with which to analyse how government can affect these trends.

METHOD

We use the data from the Federation of American Societies for Experimental Biology (FASEB, 2012) to develop a system dynamics model (Richardson, 1991; Sterman, 2000) of the postdoctoral training. The model is aimed at representing flows of different groups of the population of researchers into and out of postdoctoral positions. The specific question of effect of capping postdoc funding duration was offered by researchers at the NIH, as a part of larger efforts to understand effects of different policies on the population, productivity and diversity of research workforce development in biomedical science. Similar arguments in favour of capping duration of funding have been offered in other places (e.g. Wadman, 2012).

There has been a wide range of educationrelated system dynamics models, most of which are focused on managerial issues at the university level (Kennedy, 2011). Sterman (2000, pp.485–490) developed a system dynamics model of the pipeline of faculty promotion (assistant professor to associate to full) and replicated the promotion and exit rate of faculty members at Massachusetts Institute of Technology (MIT) between 1930 and 1993. The model was offered as an example of how a model of an ageing chain (a pipeline of people) with several simplifying assumptions can be sufficient to explain distribution of personnel at an organizational hierarchy. In another study, Larson and Gomez (2012) built a simple system dynamics model of recruitment in a university and investigated the effects of faculty retirement on hiring for faculty positions. In a follow-up study, Gomez Diaz *et al*. (2012) modelled two stages of career development, young researchers and established researchers. Overall, none of these models have specifically looked at the postdoctoral stage as a step in the ladder of training and promotion in academia, and very few have studied global or national level issues of education. This study addresses the gap and focuses on the postdoctoral phase in the pipeline of workforce development. We keep the size of the model small by focusing on the major feedback loops and the main stock–flow structure to ensure that the results of the model and the endogenous sources of the behaviors are readily communicated to policymakers (Ghaffarzadegan *et al*., 2011, p. 27; Richardson, 2013).

We use the data for three main purposes: (i) as input to the model; (ii) for model calibration and parameter estimation; and (iii) to test and examine the fidelity of the model results to observed behavior in the data. Our model simulations are used to conduct what-if analysis through testing several *policies* in the model (Bardach, 2004; Zagonel *et al*., 2004; Stewart and Mumpower, 2004; Ghaffarzadegan and Andersen, 2012). These simulation experiments include testing effects of a cap on the funding duration for PDs, an increase in faculty hiring and effects of changes in the quality of the upstream of US education, kindergarten through graduate (K-graduate). The tests emerged through discussions with NIH, reading the relevant policy discussions in the media, and through the modelling processes.

Our research procedure is as follows: first, we build a simulation model of the problem, then run the model and calibrate it with the data. After examining the model's ability in replicating the data, we perform what-if policy analyses.

MODELLING

Model Boundary

Figure 2 is a representation of research-workforce development that includes PhD students, PDs and professors in a pipeline. People enter as they are admitted to a PhD degree programme and move toward a faculty stage directly or through a postdoctoral stage. Through this path, a considerable portion of people dropout of the pipeline, graduate and go into industry, or follow other types of careers.

As depicted in Figure 2, our focus will be on the postdoctoral stage of the workforce development to address the problem of interest. Our modelling time horizon is from 1985 until 2008. We will disaggregate the model for domestic PDs versus international PDs.

In the following, we present two main aspects of the model, the feedback structure and matching mechanisms. Details of the model are presented in Tables A1–A3 in the Appendix.

Feedback Structure

Figure 3 shows a simplified causal loop diagram of the model for international PDs (group *i*). For national PDs (group *n*), we have similar feedback loops. National and international PDs are connected through matching (hiring) mechanisms.

The main stock variable is postdoc group *i*(*PDi*) represented in a box in the middle of the figure. *PDi* increases as new graduates of group *i* are recruited (in the figure, *new graduates becoming PDi*). *PDi* decreases as they find faculty positions (*PDi becoming professors*) or leave the pipeline for positions other than professorship in academia (*PDi leaving academia*).

There are four major feedback loops in this system. Two of them are related to hiring mechanisms (Loops 1 and 2). New openings are offered under two conditions: first to replace the ones that leave postdoc positions (*PD openings to fill exit rate*), and second to adjust number of PDs to organizational capacity (*PD openings for adjustment*). More openings result in more PD hiring, which ultimately increases *total PD*.

Loop 3 represents psychological, legal or economic pressures on PDs to leave a PD position for jobs outside of academia. Obviously, people cannot stay in PD positions forever: the jobs are relatively low paid, and for international PDs, there are visa-related limits for staying in the USA. As *average duration of PD* increases, people face more pressure to leave postdoc positions. The mechanism also helps formulate possible NIH imposed policies for capping duration of postdoctoral training.

Loop 4 represents the workforce development aspect of postdoctoral training. As the duration of postdoctoral training increases, researchers benefit and increase their achievements (e.g. write more papers and expand their network), and they become more likely to find permanent academic positions.

Matching Mechanisms

Through formulating matching mechanisms, we determine the proportion of openings for PD positions and faculty positions that are taken by each group of researchers.

For PD positions, PD hiring is determined as the minimum of *total PD openings* and *applicants for PD positions*. Number of applicants is a function of the number of new national and international PhD graduates who got their degree in the USA and did not land tenure-track positions, as well as international PhD graduates who got their degree outside of USA. We think it is reasonable to assume that researchers prefer to land tenure-track rather than PD positions. The portion of *PD hiring* from each group is formulated by relative weights in the market which represents the relative quality of an average new graduate from each group. We define *w* as a relative weight of an average international PhD graduate to an average national PhD graduate.

We follow a similar formulation method to formulate hiring for faculty positions. The main difference is that not only PDs compete to get a faculty position, but new graduates can also compete for tenure-track positions. Thus, we have four groups that compete, and each one can have different levels of competitiveness (weight) in the market. In each group, say international PDs, the difference between an average new PhD graduate and an average PD is the effect of PD training. It is expected that as people stay for longer periods they produce more papers, develop a better curriculum vitae and attain more capabilities, which would make them more competitive in the market (see Loop 4 in Figure 3). We define *w'* as the incremental weight that each group gains for 1 year of postdoctoral training.

Details of model formulation and the results of calibration are reported in the Appendix, Tables A1–A2. We consider *capacity for PD, PhD graduation rate* (input to *applicants for PD positions*) and *faculty openings* as exogenous variables and use longitudinal data from FASEB for these variables. Although an ideal approach is to have a model that can simulate and create these variables endogenously, we set the model boundary around postdoc training purposefully for our stakeholders' interests, which allows us to concentrate on the diversity of the population while keeping the model as simple as possible. Therefore, the main role of our model is to estimate the matching rate in a way that replicates numbers of national and international PD in the FASEB data. We use the VENSIM DSS software package, developed by Ventana Systems, Inc. (Harvard, MA, USA), for simulation and model calibration. We use longitudinal data on number of national and international PD for the pay-off function of calibration and estimate *w* and *w'*.

ANALYSIS

Base Run Simulation

Figure 4 shows simulation results and compares them with the historical trends from the data. The model is quite successful in replicating the observed data. In Figure 4(a) and (b), the simulation outputs for the number of international and national PD follow the observed trends in the data set (dashed lines) closely. The figures show that the number of international PD increases much more rapidly than national PD, which is consistent with the data. Figure 4(c) and (d) depict simulation results for the inflows to and outflows from international and national PD: PD hiring rate, PD becoming professors, and PD leaving rate from the pipeline over time.

In comparing Figure 4(c) and (d), one of the first things to observe is that on average, the rate of entrance and exit for international PD is larger than that for national PD. Furthermore, the number of PD that find a faculty position is relatively low for both international and national PDs, but the number of PDs who choose to exit the pipeline to

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presumably go into industry is increasing for both groups. These trends become more meaningful when we compare them with the hiring rate in each graph. The difference between PD hiring rate and total exit rate (i.e. sum of PD becoming professors and leaving rate) results in accumulation of PDs.

In addition to testing the fidelity of the model, we can interpret the results of parameter estimations from model calibration. The values provide some insight into the relative chances of an average person from each group in the job market. As presented in Table A2, w, relative weight of an average international researcher to a national researcher is estimated to be 1.95. This means that for a PD opening, the chance of hiring an international graduate is 1.95 / (1.95 + 1) = 0.66. Furthermore, through calibration, we estimate $w' = 1.01$. This estimation implies that if the average duration of postdoctoral training is 3 years, for a faculty position, the chance of hiring a fresh national graduate is 0.08, a fresh international graduate is 0.16, an average national PD is 0.34 and an average international PD is 0.42. We admit that these numbers are all first-order estimates based on several simplifying assumptions about distribution of the data. In the next simulations, we also report sensitivity test results for a ±50 per cent change in w to make sure our simulation experiments are robust to major changes in weights.

Policy Analysis

The model is used to examine the effects of four different policies as listed in Table 1: (i) capping the duration of funding for PDs at 4 years; (ii) capping the duration of funding for PDs at 2 years; (iii) more faculty hiring in the USA; and (iv) an increase in the quality of US K-graduate education.

These tests are implemented as counter-factual tests—that is, we compare what happened in reality (base run) with what could have happened if the policies were implemented. We pick 1995 as the base year for testing changes. Table 1 also summarizes the results of simulation runs, which we will discuss in this section in detail.

Figures 5–8 show simulation outcomes for each test, respectively. Figure 5 depicts the results of test 1: the effect of capping the duration of postdoctoral training at 4 years. The results are counter intuitive and contrary to initial expectations. Note that the number of international PDs increases [Figure 5(a): dashed line], but the number of national PDs declines [Figure 5(b): dashed line] when the duration is capped. The 99 per cent confidence interval shows robustness of the results tomajor changes in weight estimations at year 1995. This behavior is not trivial as one might expect that capping the duration should at least affect both international and national PDs in the same way, but the effects are in opposite directions.

Two main explanations can be offered for this pattern. The first is that as we cap the duration of postdoctoral training, national PDs are affected more as they are the ones who stay for a longer time in a PD career. International researchers naturally have many limitations for staying and have more incentives to leave (e.g. visa-related limitations and alterative options in their home country). Let us think of a queue of current PDs ordered according to the number of years that they have been in a PD position. As we start eliminating people who have stayed longer, US citizens who, on average, have been in PD positions for a longer time are more likely to be eliminated.

Although the reason seems logical, it does not adequately explain the results. It predicts that the numbers of both international and national PDs should decline, the latter at a faster pace. However, simulation results show that the effect of capping on international PDs is reversed and the policy will increase their numbers. How can this be possible?

The second reason that explains how the effect of the policy on international PDs can be reversed is linked to the feedback structure of the system. Let us imagine what will happen if a project manager is asked not to fund her long-time PD anymore? Will the project manager stop the project? Will she do the rest of the project by herself? Of course not; it is likely that she will hire a new PD. Now let us think about our model of national and international PDs. As long-time national PDs encounter the cap and leave, more empty slots become available for new PDs. This structure was presented in Figure 3 (Loop 1). In the competitive market, international PDs would take a considerable portion of the new positions. As stated, the model predicts that the ratio of new PD hires from international scholars to be 66 per cent. In other words, capping the duration mostly eliminates national PDs with longer durations, and offers many empty slots to new international PhD graduates.

Test 2 takes an extreme-condition approach by capping the duration of PD at 2 years. The results are depicted in Figure 6. In the extreme condition, both groups would be affected as there are not enough candidates in the job market for PD positions to replace the ones that leave. But as the figure shows, overall, the effect on national PDs is much larger, so the proportion of national versus international PDs changes in favour of international PDs.

Notice that the results are not sensitive at all to changes in relative weights as the 99 per cent confidence interval is very narrow. The reason is that in this extreme condition test, the harsh strategy of 2 year cap results in too many openings to fill the exit rate, which will be more than number of applicants. So, basically almost everybody is hiredno matter what the average quality is.

In summary, Tests 1 and 2 suggest that capping the duration of PD results in a higher ratio of international to national PDs.

In Test 3, we analyse the effects of a change at the end of the pipeline. There is a common argument that most of the problems regarding PD careers concern the lack of faculty positions. We test the effects of more faculty openings. Figure 7 shows the results. This policy has very little effect on the trends.

All of these tests show that changing the balance in the system in favour of domestic workforce is difficult and the suggested policies can backfire and act contrary to what we expect. The declining rate of national PDs might relate to being less competitive in the job market, which may be rooted in the education system. Our model does not look at the upstream part of the pipeline. However, to represent a change in upstream, we can increase the relative competitiveness of US graduates to international graduates. Such an increase, Test 4, will represent a rise in the output quality of the K-graduate pipeline, which is the input to the PD positions. Figure 8 shows the results. Higher quality national graduates will increase the proportion of national PDs.

DISCUSSION

In this paper, we analysed the trends of national versus international postdocs in the USA. We built a system dynamics model of postdoctoral training. Then, we calibrated the model with data from FASEB. Our model successfully replicated the observed trends in the data. Using the calibrated model, we then conducted what-if analyses and examined the conditions under which the ratio of international to national PDs changes.

This study offers three major contributions. First, the paper contributes to the studies of PD population in academia. Earlier studies mostly looked at effects of postdoctoral training on researchers' performance (Gentile *et al*., 1989; Levey *et al*., 1988; Steiner *et al*., 2002; Su, 2011; Zumeta, 1984, 1985). Our study mainly connects to the ones that address the increasing numbers of PDs and compare decision-making behaviors of national versus international scholars (Wei *et al*., 2012; Lan, 2012; Cantwell & Lee, 2010). We offer a stock–flow perspective to how the population of PDs is increasing and to how the balance between national and international PDs is changing. Then based on a few major feedback mechanisms, we represent hiring decision rules that affect flows of researchers into PD positions and the transition from PD into faculty positions.

Second, the paper contributes to the modelling literature of research workforce. Building on the past models (Sterman, 2000, pp.485–490; Larson and Gomez, 2012; Gomez Diaz *et al*., 2012), this study offers the first simulation model of research workforce development that focuses on postdoctoral training. The model is formulated and could be applied to different segments of the PD population to study dynamics of gender and race diversity across the population of PDs.

Third, using the model, we conducted several simulation-based analyses of various policies for research workforce development. Our model showed that capping the duration of a postdoctoral career is likely to have an unintended effect of favouring foreign PDs and decreasing the ratio of national to international PDs in the USA. No formal analyses prior to this study investigated the possible effects of these policies. We also explored effects of higher recruitment in academia and more competitiveness in the market on the diversity of PDs.

Similar to all modelling efforts, the current study faces several limitations. Our model boundary is defined around PD training and does not consider the upstream aspects of the education pipeline such at the high school stage in detail. Apparently, the K-graduate stage seems to play a crucial role in research workforce development. We conducted a simple experiment to see effects of an upstream change, but more in-depth analyses would require expansion of the model to include dynamics, delays and feedback structures around the K-graduate stage.

Furthermore, there are other feedback loops that are interesting and can represent complex issues in this system. For example, the capacity for PDs might be affected as more experienced PDs leave. We assumed the numbers to be exogenous to the model. Also, we used an average weight to represent the relative capabilities of different groups of individuals. These values might change because of exogenous factors (e.g. economic growth in the home county of international scholars) or endogenous factors (e.g. as more international scholars are hired, the average quality of the remaining group decreases). However, our sensitivity analysis showed robustness of our results to 50 per cent change in relative weights. Adding more details to the characteristics of researchers, for example, differentiating them based on years of experience, gender, country of origin and university might add more insights at the expense of making the model more complicated. Although the simplifications are in line with the scope and goal of the current study, they also suggest future avenues of research.

In summary, our analysis shows that the leverage point to affect diversity in the research workforce development system is in the K-graduate education area and policies implemented at the postgraduate level have minimal effects, or contrary to what we expected, on diversity. Specifically capping the duration of postdoctoral training could have unintended effects and result in decreasing the ratio of national to international PDs in US academia. The reason lies in a feedback loop that represents the way that project managers might respond. They are likely to replace the old PDs who are more likely to be domestic by hiring new graduates who are more likely to be from the international pool of researchers. This reaction will further decrease the ratio of national to international PDs. Effects of this feedback loop have been underestimated in the policy debates.

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APPENDIX

Table A1

Model formulation[b]

Notation	Description	Formulation
PD_g	PD group g, g ∈ {national (n), international (i)}	$PD_g = \int (p_g - (f_g + e_g))dt + IPD_g$
p_g	Hiring PD group g	$p_g = p \cdot \alpha_g$
f_g	PD group g becoming professors	$f_g = f \cdot \beta_g$
e_g	PD group g leaving the pipeline	$e_g = (PD_g - f_g) \cdot S(h(T_{Max,g} - T_g), 1, 0.5)$ • $S(x, 1, 0.5)$ = smoothing x with a delay of 1 and initial value of 0.5. It represents the delay it takes to change job.
T_g	Average time in PD	$T_g = PD_g/(f_g + e_g)$

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Notation	Description	Formulation
p	Total hiring for PD	$p = \min(G_i^- + G_n^-, O_{PD})$
O_{PD}	Total openings for PD	$O_{PD} = max(0, e_i + e_n + f_i + f_n + (CPD - PD_i - PD_n)/\tau)$
α_g	Proportion of hiring for PD positions from group g	$\alpha_i = \min\left(\frac{w}{1+w}, \frac{G_i^-}{p}\right)$ $\alpha_n = \min\left(\frac{w}{1+w}, \frac{G_n^-}{p}\right)$
$\bar{\alpha}_g$	Adjusted proportion of hiring for PD positions from group g	$\bar{\alpha}_i = \min\left(1 - \alpha_n, \frac{G_i^-}{p}\right)$ $\bar{\alpha}_n = \min\left(1 - \alpha_i, \frac{G_n^-}{p}\right)$
G_g^-	New graduates of group g in PD market	$G_g^- = G_g - G_g^*$
G_g	New PhDs of each group that are potential candidates for a PD or a tenure-track position	$G_i = (k + k') \cdot PhD_i$
G_g^*	New PhDs that land tenure-track positions	$G_g^* = f \cdot \gamma_g$
f	Total hiring for faculty positions	$f = \min(G_i + G_n + PD_i + PD_n, O_F) \approx O_F$
γ_g	Proportion of hiring for faculty positions from new PhDs	$\gamma_i = \frac{w}{1 + w + \left(1 + \tilde{w}_n\right) + \left(w + \tilde{w}_i\right)}$ $\gamma_n = \frac{1}{1 + w + \left(1 + \tilde{w}_n\right) + \left(w + \tilde{w}_i\right)}$
β_g	Proportion of hiring for faculty positions from PDs	$\beta_i = \frac{w + \tilde{w}_I}{1 + w + (1 + \tilde{w}_n) + (w + \tilde{w}_i)}$ $\beta_n = \frac{1 + \tilde{w}_n}{1 + w + (1 + \tilde{w}_n) + (w + \tilde{w}_i)}$
$w\sim_g$	Effect of time spent in PD on one's competitiveness	$w_g = S\left(w' \cdot T_g, 1, 4w'\right)$ • $S(x, 1, 4w')$ = smoothing x with a delay of 1 and initial value of $4w'$ (initial PD length is assumed to be 4 years). It represents the delay in publication process.

PD, postdoc.

[b] The table is a compressed presentation of all formulations of Vensim to replicate the results in other softwares. The model in Vensim is available from the first author.

Table A2

Parameters and exogenous variables

Notation	Description	Value	Source
IPD_g	Initial number of postdocs in group g	3398 for international. 6805 for national.	FASEB
$T_{Max,g}$	Maximum time in postdoc	For no-cap regulation (base run): 6 for international and 20 for national (no limit) For policy tests, based on Table A3	Assumption based on visa duration rules for temporary residents. What-if tests
w	Relative weight of internationals to nationals	1.95	Calibration
w'	Incremental gain for a year of postdoc	1.01	Calibration
k	Ratio of international graduates in USA interested to stay in the USA	0.75	NSF website and authors' estimation
k'	Ratio of international grads in foreign countries interested in US postdoc positions to international grads in the USA	4.5	FASEB
O_F	Faculty openings	Time series of hiring	FASEB
CPD	Capacity for postdocs	Time series of total number of postdocs	FASEB
PhD_g	National and international PhD graduation rate in the USA	Time series of number of PhD graduates	FASEB
h	Table function to represent effects of time pressure on leaving postdoc	h ((0,1), (0.5,0.95), (0.8,0.8), (1,0.55), (1.22,0.33), (1.5,0.2), (2,0.1))	Authors' assumption
τ	Time to adjust capacity	1 year	Authors' assumption

FASEB, Federation of American Societies for Experimental Biology.

Table A3

Operationalization of the simulation experiments

Tests	Operationalization	Parameter values for test
Test 1	Change $T_{Max,g}$ (maximum time to stay in postdoc)	After year 1995: $T_{Max,g} = 4$ *years*
Test 2	Change $T_{Max,g}$ (maximum time to stay in postdoc)	After year 1995: $T_{Max,g} = 2$ *years*
Test 3	Change O_F (faculty openings), at time = 1995	After year 1995: multiplied by 2.
Test 4	Change w (relative weight of internationals to nationals) at time 1995	After year 1995: $w = 1$.

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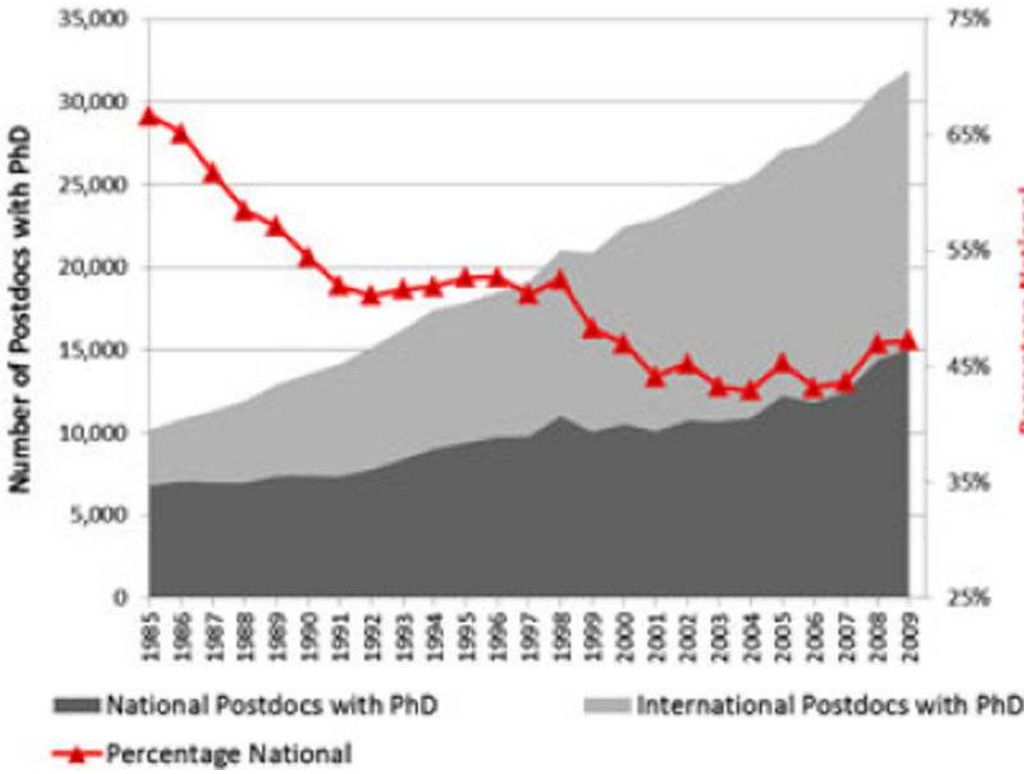

Figure 1.
The trend of postdoc researchers in biology and medicine with PhD for national versus international scholars (Source: FASEB (2012))

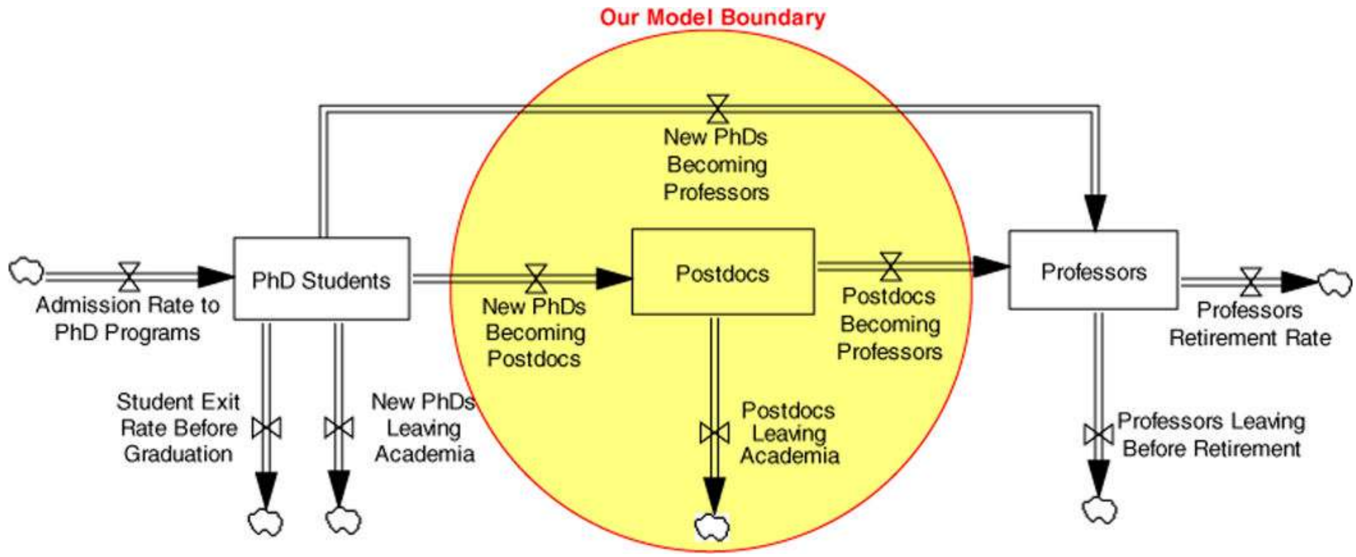

Figure 2.
Research workforce pipeline and the modelling boundary

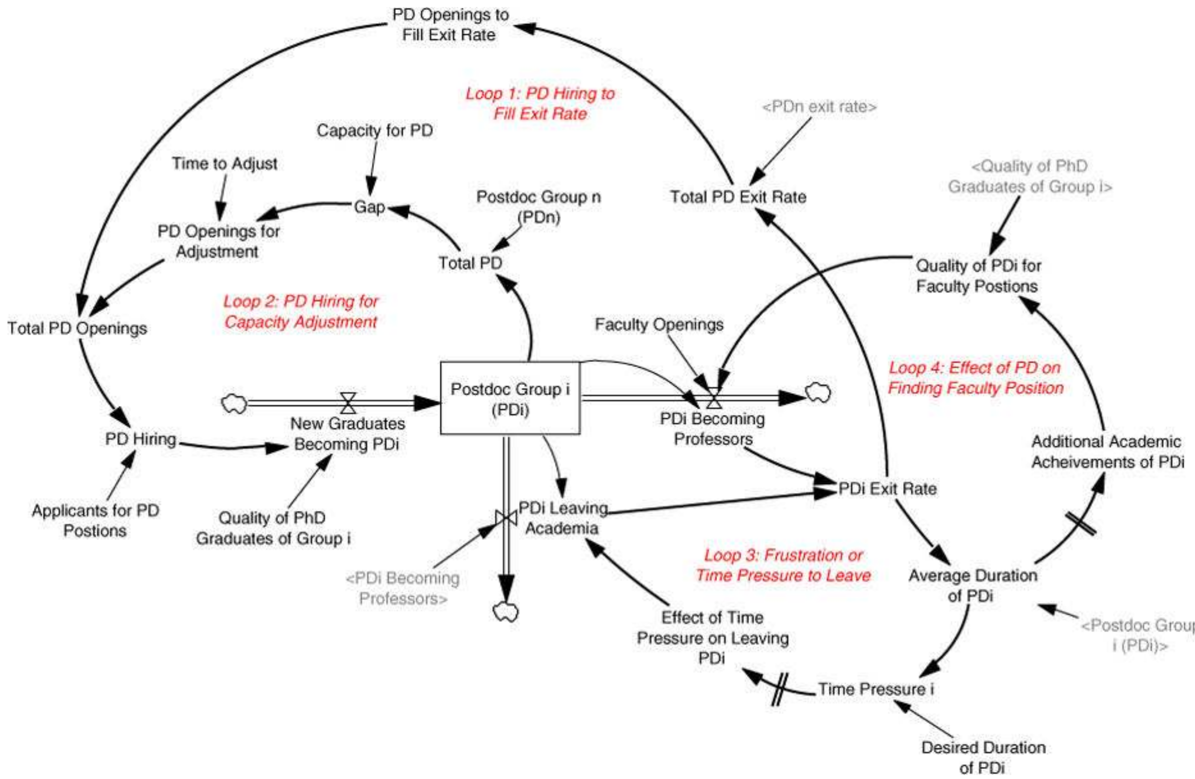

Figure 3.

Causal loop diagram of hiring and exit rate of postdoc group i

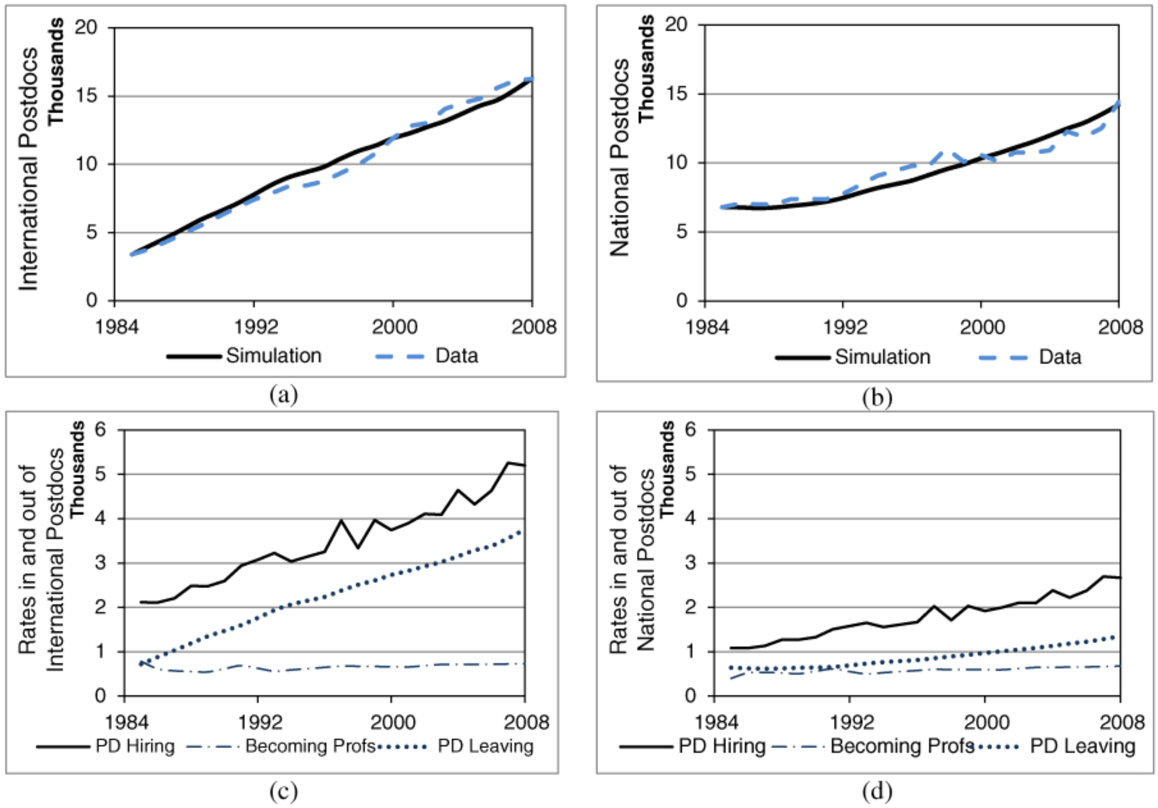

Figure 4.
Simulation results for the base run

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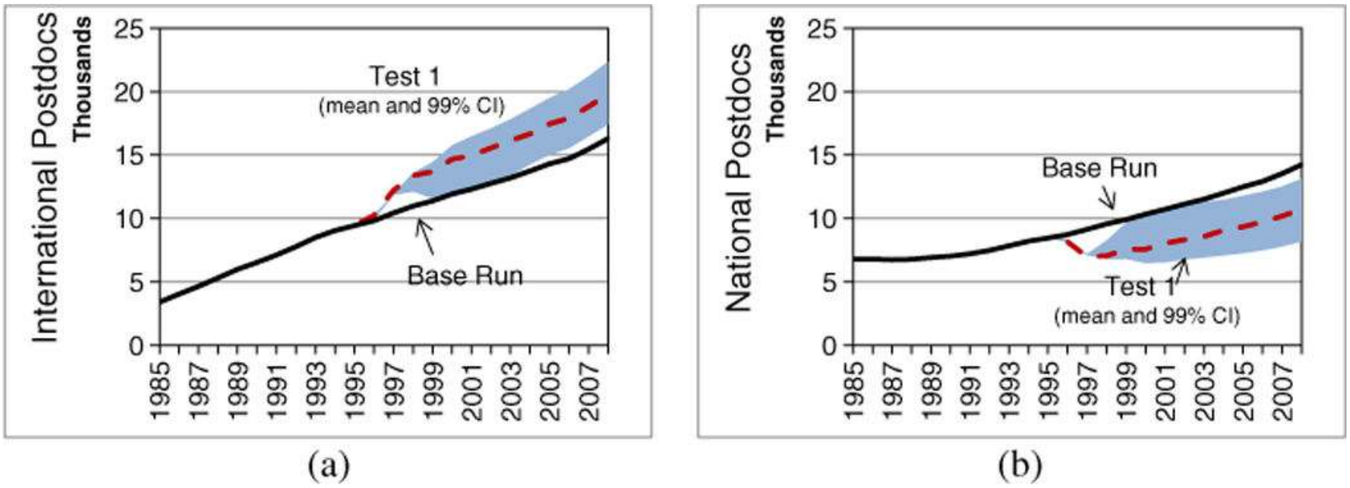

Figure 5.

Test 1: capping the duration of postdocs in 1995 at 4 years

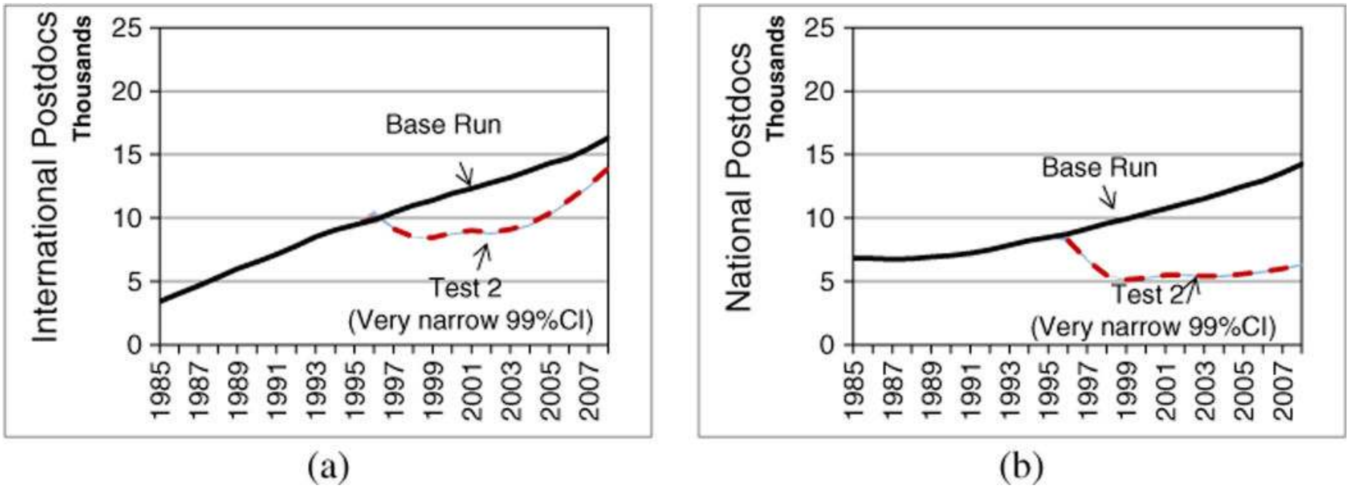

Figure 6.
Test 2: capping the duration of postdocs in 1995 at 2 years

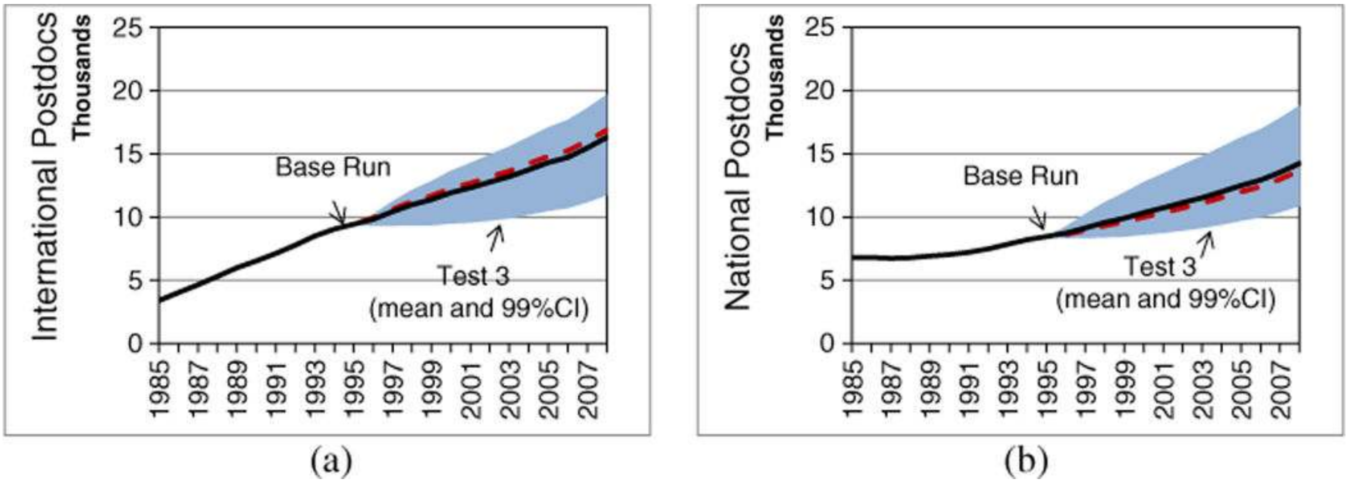

Figure 7.
Test 3: what if more faculty jobs were available

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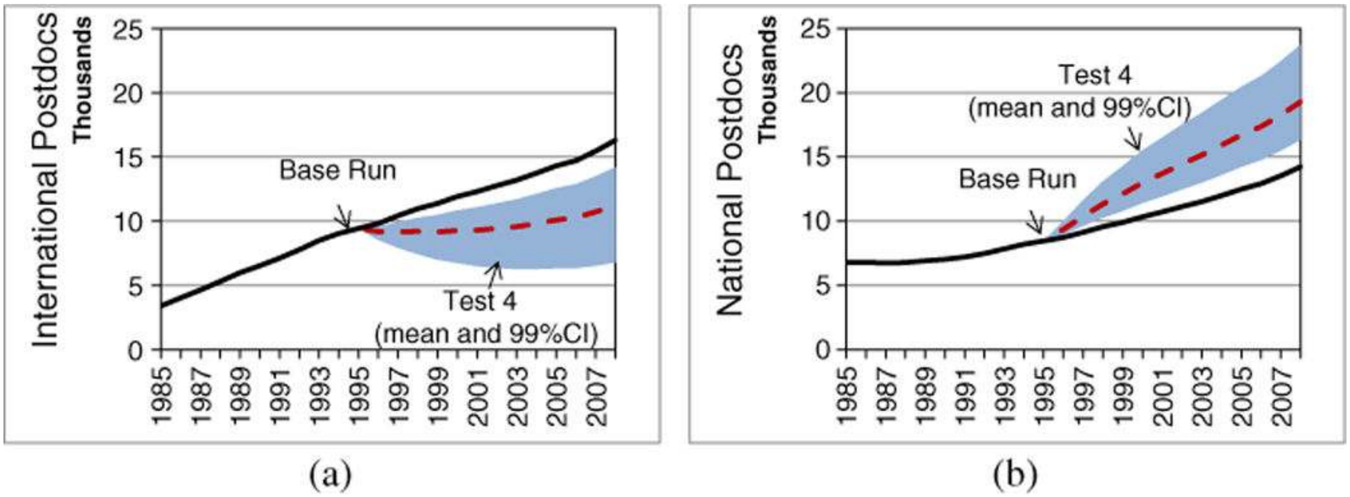

Figure 8.
Test 4: what if domestic graduates were more competitive

Table 1

Four simulation experiments and directions of their effects on different policy measures

	Policy measures			
Simulation experiments	**International postdocs**	**National postdocs**	**Ratio of national to international postdocs**	**Faculty hiring ratio of national to international scholars**
(1): Capping duration of postdoc at 4 years	↑	↓	↓↓	↓↓
(2): Capping duration of postdoc at 2 years	↓	↓↓	↓↓	↓
(3): More faculty hiring in the USA	↑	↓	↓	↓
(4): Increase in the quality of US K-graduate education	↓	↑	↑↑	↑↑