Closing the Ph.D. Talent Gap in Taiwan: A Macroeconomic Analysis*

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Abstract

Taiwan is experiencing a decline in the number of doctoral students and aging faculty members in higher education. How to provide incentives for students to pursue a doctoral degree becomes a widely discussed issue. This paper constructs an occupational choice model with overlapping and heterogeneous individuals rationally choosing to study abroad, enter domestic doctoral programs, or work in the industry. The framework captures the features of the two-stage Ph.D. labor market and the spillover effect of knowledge production on the industry sector. We also highlight the productivity differential between overseas-trained professors and their domestic counterparts. The model is used to quantify the effects of various subsidies on higher education. Our quantitative analysis suggests that providing a subsidy to domestic doctoral students is more effective in boosting the number of doctoral students than subsidizing professors' research. Nevertheless, in the fields with a relatively large productivity differential, this policy does not necessarily improve the average welfare because of fewer overseas-trained professors and lower knowledge accumulation.

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1 Introduction

Over the past decade, Taiwan's higher education has undergone notable transformations. The number of students enrolled in Ph.D. programs peaked at 34,105 in 2010 but subsequently experienced a decline, resulting in a 16 percent reduction from the peak by 2022. In addition, Taiwan's lowest-low birth rate is causing a decline in college students, which could worsen the shortage of individuals pursuing doctoral degrees in the future.[1] Meanwhile, concerns have been raised about the aging faculty in higher education, with over 60 percent of faculty members being over 50 years old in 2019, up from 42 percent in 2012.[2] This trend is in contrast to Japan and the UK, where the percentage of faculty members over age 50 remained stable in Japan and declined in the UK, despite starting at a similar level to Taiwan in 2012.[3] The lack of individuals pursuing doctoral degrees and the aging faculty members raise concerns about Taiwan's research productivity and consequently labor productivity in the long run. In response, some subsidies have been proposed to increase the number of doctoral students. To understand the motivations for pursuing a doctoral degree, this paper seeks to model the features of the Ph.D. labor market and quantify the effects of various subsidies to Taiwan's higher education on the incentive to pursue doctoral degrees, knowledge accumulation, labor productivity, and average welfare.

The Ph.D. labor market is distinct from the regular labor market due to its longer training period and the requirement of a Ph.D. degree to obtain a faculty position.[4] In addition, Sauermann and Roach (2012) found that the majority of doctoral students aim to pursue academic careers in research and teaching. However, Cyranoski et al. (2011) reported that only 15 percent of science Ph.D. in the US were able to secure a tenure-track position within six years after graduation, indicating that obtaining a faculty position may be quite uncertain. Therefore, those who choose to pursue a Ph.D. bears the opportunity cost of not working in industry during their studies and the uncertainty of obtaining a faculty position after graduation.

To capture the features of the Ph.D. labor market, we adopt an approach of macroeconomic analysis. Our model is based on Samuelson's (1958) overlapping-generations (OLG) structure, in which doctoral students and professors are overlapped. Based on the calibers they obtain, individuals de-

[1] The lowest-low birth rates affect Taiwan's higher education via both the demand and the supply side. On one hand, the lower fertility rate results in a decline in the demand of the higher education. In general, there are at least two possibilities that could lead to this phenomenon. The first case is a lower fertility rate but a stable enrollment rate of undergraduates. This is exactly the experience of Taiwan. Secondly, a decline in the number of undergraduates could be directly due to a decreasing enrollment rate of undergraduates, while the fertility is slightly increasing, relatively stable, or decreasing. Using the gross enrollment ratio in tertiary education from the Our-World-in-Data, we find that there were 38 countries that experienced a decline in the gross enrollment ratio in tertiary education during 2012-2022. Hence, our paper can be applied to countries experiencing a decrease in the growth of undergraduate student populations, regardless of the underlying causes for this decline. On the other hand, the low fertility rate in Taiwan also causes a decline in the supply of the higher education due to lower incentives for students to pursue doctoral degrees. See Appendix A for further discussions.

[2] Source: National Profiles of Human Resources in Science and Technology (NPHRST), 2022.

[3] Figure A1 provides the detailed age structures of faculty members in Japan, Taiwan, and the UK.

[4] The Ph.D. labor market also stands apart from other professional labor markets that require long periods of training due to its emphasis on original research during and after the training period, as pointed out by studies such as Stuen, Mobarak, and Maskus (2012) and Gaulé and Piacentini (2013).

cide to study abroad as international doctoral students, enter domestic doctoral programs, or work in the industry as workers. Being doctoral students face two risks: not able to graduate from the doctoral program and the uncertainty of securing a faculty position after graduation. In either case, they would become workers in the industry. The Ph.D. labor market is divided into two stages. In the first stage, individuals decide to become domestic doctoral students and faculty members hire domestic doctoral students to produce knowledge. In the second stage, individuals graduate from doctoral programs and seek faculty positions in the domestic market. The available faculty vacancies at this stage are determined by the demand for higher education. Furthermore, we allow for a productivity differential in knowledge production between professors who received doctoral training abroad or domestically.[5] We also account for a difference in the likelihood of international and domestic doctoral graduates seeking academic faculty positions, which has been observed in Taiwan and South Korea (Jung, 2018). In general equilibrium, the numbers of individuals with different occupational choices are endogenously determined. Then, labor allocations, output in the industry sector, and knowledge accumulation in the economy are determined accordingly.

The importance of Ph.D. holders has increased significantly in the modern economy, as it is closely linked with driving innovation, accumulating knowledge, and advancing technology. This trend originated in Germany during the early nineteenth century when conducting original research became mandatory for obtaining a Ph.D. Today, acquiring a Ph.D. is a prerequisite for securing a faculty position at universities, which are responsible for the majority of higher education and knowledge production. Moreover, companies that rely on research and development to remain competitive have a growing preference for Ph.D.-holding employees. As Lucas (2009) argued, the accumulation of knowledge has a spillover effect on productivity growth.[6] Therefore, due to the externality of knowledge creation (Klenow and Rodríguez-Clare, 2005), the aforementioned transformation in higher education in the past decade of Taiwan could negatively affect the whole economy.

The above concerns have led to a continuing discussion about the talent gap in higher education and appropriate policy reforms. For example, Academia Sinica (2023) proposed possible policies including subsidies to doctoral students and professors. It is natural to ask how such policies are effective in bridging the talent gap in Taiwan. To answer this question, our next step is to quantitatively evaluate the impacts of these policy reforms on individual occupational decisions and the economy. However, collecting data on the occupational choices of doctoral students is crucial for discussing issues and policies in the Ph.D. labor market (Kelly and Marians, 2014). Due to data limitations, few studies have analyzed this market (Ehrenberg, 1992). To fill this gap, our paper collects data from Taiwan between 2006-2015 for quantitative analysis. There are two characteristics of Taiwanese data. First, professors' salaries within a specific rank are nearly equal, and the information is accessible to the public. Therefore, the uncertainty of lifetime income for doctoral students mainly comes from the two risks mentioned above. Second, the supply of domestic doctoral graduates can be explicitly

[5] The productivity differential can be attributed to the varying opportunities for international collaboration and capabilities of international mobility (Sambunjak and Marušić, 2011; Petzold and Peter, 2015).

[6] The spillover effect has been identified by economic research such as Moretti (2004) and Gennaioli, La Porta, Lopez-de-Silanes, and Shleifer (2013).

estimated, since most of them only search for faculty positions in Taiwan during the periods we examine. Furthermore, a policy reform may have varying effects on different fields. To emphasize the variations across fields, the model is calibrated in various disciplines, including engineering, science, medical sciences, humanities, social sciences, and the combined representation of these five fields, which is referred to "the aggregate".

In practice, a subsidy to professors through research grants is commonly used, such as in China and France (Altbach, Reisberg, Yudkevich, Androushchak, and Pacheco, 2012). Alternatively, a subsidy to domestic doctoral students has been adopted in Taiwan, Norway, Sweden, and the UK.[7] We quantify these two subsidies and find that the subsidy to domestic doctoral students is more efficient in boosting the input in knowledge production, i.e., the number of domestic doctoral students. This is because a subsidy to professors' research is less attractive to individuals who pursue a doctoral degree since they face the two risks of becoming professors. However, our quantitative result also suggests that the subsidy to domestic doctoral students brings two opposite effects on knowledge production: it increases the number of domestic doctoral students but decreases the share of professors who have higher productivity due to overseas training. Our analysis shows that the former dominates the latter effect if the productivity differential is negligible. Thus, we find that in the fields with relatively minor productivity differentials, such as medical sciences and humanities, the subsidy to domestic doctoral students promotes the accumulation of knowledge and output in the industry sector. In contrast, the subsidy reform could result in lower knowledge accumulation and less output when the productivity differential widens.

To measure the productivity differentials of doctoral graduates among countries, we choose the h-index rankings from the SCImago Journal & Country Rank (SJR) to compare research productivity in different countries. The h-index suggests that the US, UK, Sweden, Norway, and Taiwan have the rankings of #1, #2, #13, #20, and #29, respectively.[8] Therefore, it can be stated that the productivity differential between Taiwan and the US is greater than that between the US and the UK, Sweden, or Norway. To further examine the role of productivity differential in our policy analysis, we conduct a counterfactual analysis without the productivity differential. The result shows that, taking the aggregate field as an example, a subsidy to domestic doctoral students not only increases the number of domestic doctoral students, but also brings a higher level of knowledge accumulation and improves the average welfare. The intuition is that the negative effect of productivity differential on knowledge production disappears in the scenario. Thus, an increase in the number of domestic doctoral students

[7] In Taiwan, the Ministry of Science and Technology grants 40,000 TWD per month to each selected doctoral student from all fields. In Norway and Sweden, there are no tuition fees. All doctoral students receive a salary that is almost equal to being a junior faculty member (Williams, Jones, Jonsson, Harris, and Mulvany, 2019); moreover, the duties include engagement in teaching for 20 percent of their time (Bröchner and Sezer, 2020). In the UK, a government-funded studentship not only covers doctoral students' tuition fees but also provides at least 15,609 GBP per year for living expenses. Students from all fields can apply for this studentship. Detailed information can be found at https://www.ukri.org.

[8] SJR provides indicators that can be used to assess and compare scientific domains in different countries (SCImago, 2021). The h-index is a citation-based indicator, which is shown to have the power to predict researchers' labor market outcomes (Ellison, 2013). However, the SJR data is not sufficient for calibrating a model, so we use research grants funded by the government as a proxy to measure the knowledge output of a professor in our quantitative analysis.

leads to a higher level of knowledge accumulation, thereby larger output and welfare improvement. Nevertheless, when we extend the counterfactual analysis to scenarios with the existence of larger productivity differentials, professors' superior productivity from overseas training becomes important to knowledge production. Therefore, the subsidy to professors' research could bring to a higher level of knowledge accumulation and output, rather than a subsidy to domestic doctoral students.

Similar to this paper, Akcigit, Pearce, and Prato (2020) study the effect of education policies as well as research subsidies on innovation and growth. They build an endogenous growth model in which individuals have different talents for research, but talented individuals may not pursue a research career due to preferences or financial frictions. They calibrate the model with data from Denmark and show that research subsidies have limited impact on innovation in the long run unless combined with education policies to encourage talented but financially constrained youth pursuing a Ph.D. degree. Our results align with their findings in that research subsides to professors could be less effective than subsides to doctoral students in promoting knowledge production, depending on the productivity differentials.

To our knowledge, this paper is the very first study using the OLG structure to model occupational choice in the Ph.D. labor market. In the economic literature, previous studies of occupational choice focus on expectation formation, such as adaptive expectation in Freeman (1975) and rational expectation in Siow (1984). Ryoo and Rosen (2004) indicate that the rational expectation hypothesis is well suited to the data in the US engineering market. Nevertheless, Manski (1993, 2004) argues that observed data may be consistent with some alternative specifications of expectation formation. Betts (1996), Jensen (2010), and Zafar (2011) find that students have biased beliefs about market wages, but Wiswall and Zafar (2015) show that students rationally revised their beliefs in response to new information. Moreover, Llull (2017) demonstrates a labor adjustment in education years in response to supply shocks. In our model, individuals are rational, similar to that for public school teachers in Zarkin (1985), where the demand for professors can be estimated by the number of existing students. The demand for professors is known to individuals when they are determining their occupational choices.

The rest of the paper proceeds as follows. Section 2 presents the model and the steady-state equilibrium. Based on Taiwanese data, Sections 3 and 4 discuss the calibration and policy experiments for various subsidies. Section 5 provides counterfactual analysis for varying productivity differentials between overseas-trained and domestically-trained professors. Section 6 concludes the paper and discusses possible extensions.

2 Model

The world consists of two regions: a home country and the rest of the world. Our analysis focuses on the home country, while also considering the opportunity for students to pursue a doctoral degree abroad, specifically as international doctoral students. The home country has two sectors: an academic knowledge production sector and an industry sector. Under this setting, we develop a general equilibrium five-period OLG model in which the first period and the rest of the periods refer to the young and old periods, respectively.[9] In the young period, an agent chooses to be an international doctoral student, a domestic doctoral student, or a young worker. A young worker will surely become a worker in the old periods. A doctoral student, however, may become a professor, a worker, or a Ph.D. worker in the second period, and then the occupation is assumed to be unchanged in the rest periods. In the economy, on the one hand, professors hire domestic doctoral students as labor inputs for knowledge production in the academic sector. The accumulation of knowledge will contribute to labor productivity in the industry sector. However, professors and their doctoral students only share the value of new knowledge, which captures a distinct feature of the academic sector emphasizing original research. Thus, a spillover effect exists, which comes from the contribution of the accumulated knowledge in previous periods. On the other hand, the supply of domestic doctoral students is determined by agents' occupational choices. That is, an agent compares the expected lifetime utility among three options: being a domestic doctoral student, becoming an international doctoral student, or being a worker. In this section, we formally describe the model. The steady-state equilibrium is presented in Section 2.5.

2.1 Occupational State

Time is infinite and discrete, $t = 1, 2, 3, \cdots$. At the time t, there is a continuum of new agents (hereafter generation t) who enter the economy and live for five periods in the home country. Let n_t be the size of generation t, and $g > 0$ be the gross rate of generation growth; hence $n_{t+1} = gn_t$. Note that the size of generation t is interpreted as the number of undergraduate students, rather than the count of newborn babies. In the first period, an agent can choose to be a worker or a doctoral student. Moreover, two options are available for doctoral studies: a domestic doctoral student studying in the home country or an international student pursuing a doctoral degree abroad.[10]

In the second period, young workers will become old workers for sure. However, doctoral students will become professors or workers. Let $i \in [0, n_t]$ be the index of agents and $f_t(i)$ be the probability of graduation in the Ph.D. program such that $f_t'(i) < 0$ for agent $i \in [0, n_t]$. That is, the higher an agent's index, the lower the chance he or she can graduate from a Ph.D. program. In addition, $p_{\mathbb{I},t+1}$ denotes the probability of finding an academic faculty position, where $\mathbb{I} \in \{0, 1\}$ is an indicator function in which $\mathbb{I} = 0$ indicates having a domestic doctoral degree and $\mathbb{I} = 1$ indicates having an international doctoral degree.[11] Moreover, if a doctoral student graduates from a Ph.D. program and then works in the industry sector, he or she will be a Ph.D. worker. Therefore, a doctoral student i of generation t will become a professor, a worker (entering a Ph.D. program but not able to graduate), or a Ph.D. worker with the probability of $f_t(i)p_{\mathbb{I},t+1}$, $1 - f_t(i)$, and $f_t(i)(1 - p_{\mathbb{I},t+1})$, and earn salaries or wages (henceforth, wages) of d_{t+j}, w_{t+j}, and κw_{t+j} for $j \in \{1, 2, 3, 4\}$, respectively. We define $\kappa \geq 1$ as the wage premium for a Ph.D. worker.[12]

[9] The five-period setting matters for the calibration, as it allows us to match the average lengths of being doctoral students and professors in data.

[10] Domestic and international doctoral students face different constraints, which will be discussed in Section 2.4.

[11] The assumption of $f_t'(i) < 0$ captures individuals' heterogeneous caliber regarding the graduation rate.

[12] The wage premium reflects the market value of Ph.D. training in the industry, which can vary across fields. It is also

2.2 Two-Stage Ph.D. Labor Market

There are two stages of the labor market in the academic sector over an agent's life cycle. In the first stage, professors hire domestic doctoral students for knowledge production. The supply of doctoral students comes from agents who choose to enter domestic doctoral programs.[13] After one period, the doctoral graduates of generation t look for faculty positions in the second-stage labor market. At this stage, the demand for higher education (therefore, the faculty vacancies) is determined by the number of generation $t+1$, and the supply comes from domestic and international doctoral graduates. The details are described as follows.

In the first-stage labor market, each professor has a demand for $m_{\mathbb{I},t}$ domestic doctoral students, where $m_{0,t}$ is the demand of a professor with a domestic doctoral degree and $m_{1,t}$ is the demand of a professor with an international doctoral degree. Let ε_t and $\mu_t - \varepsilon_t$ be the proportions of generation t who choose to be international and domestic doctoral students, respectively. This implies that the proportion of generation t who become doctoral students is μ_t. Because agents' occupational choices are sorted by their calibers, domestic and international doctoral students face different average graduation rates and the graduation rates are correlated to their calibers. Specifically, we define $q_{\mathbb{I},t}$ as the average graduation rate for domestic and international doctoral students of generation t. Then, the average graduation rate for domestic doctoral students is given by

$$q_{0,t} = \frac{\int_{n_t\varepsilon_t}^{n_t\mu_t} f_t(i)\,di}{n_t(\mu_t - \varepsilon_t)},$$

and the average graduation rate for international doctoral students is

$$q_{1,t} = \frac{\int_{0}^{n_t\varepsilon_t} f_t(i)\,di}{n_t\varepsilon_t}.$$

Moreover, we denote $R_{\mathbb{I},t}$ as the total number of professors working in the academic sector of the home country at time t. They were doctoral graduates in the past four periods. Therefore, the number of professors with domestic doctoral degrees is given by

$$R_{0,t} = \sum_{j=t-4}^{t-1} n_j(\mu_j - \varepsilon_j)q_{0,j}p_{0,j+1};$$

and the number of professors with international doctoral degrees is

$$R_{1,t} = \sum_{j=t-4}^{t-1} n_j\varepsilon_j q_{1,j}(1-\zeta)p_{1,j+1},$$

related to the policy suggestion of Daniels (2015) to diversify Ph.D. training for nonacademic needs. It is worth to note that our setup implies the human capital of workers without Ph.D. degrees is normalized to be one. In addition, our model allows $p_{0,t+1} \neq p_{1,t+1}$ to reflect the difference in prestige between domestic and foreign graduate schools.

[13] In reality, there are Ph.D. quotas in Taiwan's higher education. However, from the perspective of the national level, the Ph.D. quotas were not binding during the periods that we examine. Therefore, in our setting, the equilibrium number of domestic doctoral students is endogenously determined by the demand and supply in the market. See Appendix A.2 for further discussions.

where $0 < \zeta < 1$ is the ratio of brain drain. This assumption captures the fact that students studying abroad may not return to the home country. We also define $p_{0,j+1} = p_{j+1}$ and assume that $p_{1,j+1} = \alpha p_{0,j+1}$, where $\alpha > 1$ (or $\alpha < 1$) captures the advantage (or disadvantage) of finding faculty positions for international doctoral graduates. The market-clearing condition in the first-stage market at time t is hence given by

$$m_{0,t}R_{0,t} + m_{1,t}R_{1,t} = n_t(\mu_t - \varepsilon_t),$$

where the right-hand side $n_t(\mu_t - \varepsilon_t)$ represents the supply of domestic doctoral students, which is determined by the occupational choices of generation t. We will further discuss an agent's occupational choice in Section 2.4.[14]

In the second-stage market at time t, each young agent needs one unit of higher education. On the other hand, each professor provides a units of higher education. That is, we do not differentiate the ability of teaching between domestic and international doctoral graduates.[15] Therefore, the market-clearing condition in the second-stage market is

$$n_t = a(R_{0,t} + R_{1,t}).$$

It is worth to note that both domestic and international doctoral graduates enter the domestic market at this stage. Some will obtain faculty positions, while others will become Ph.D. workers.

2.3 Production Sectors

There are two sectors in the home country: academic and industry sectors. The output of the academic sector is new knowledge. The accumulated knowledge becomes one of the inputs in the industry sector. We first describe the academic sector and then discuss the industry sector.

For a professor, new knowledge $x_{\mathbb{I},t}$ is produced by a generalized CES technology:

$$x_{\mathbb{I},t} = \left[(1-\phi_x)B_{\mathbb{I}}r_t^{\theta_x} + \phi_x m_{\mathbb{I},t}{}^{\theta_x}\right]^{\lambda/\theta_x},$$

where $0 < \lambda \leq 1$ is the degree of returns to scale; $\phi_x \in (0,1)$ is the share parameter; and θ_x is an elasticity parameter, where $1/(1-\theta_x)$ is the elasticity of substitution between the professor's research time (r_t) and doctoral students' labor. The value of θ_x is less than or equal to one and can be $-\infty$. The parameters $B_0 > 0$ and $B_1 > 0$ represent the research efficiency of the professor's research time. We allow $B_1 \neq B_0$ to differentiate the productivity efficiency between domestic and international doctoral graduates. In addition, we assume that the professor's research time is fixed and normalized to 1. That is, $r_t = 1$.

[14]It is worth to note that an agent makes an occupational choice by comparing the expected lifetime utility of directly being a worker, entering domestic doctoral program, and pursuing a Ph.D. degree overseas. Therefore, the first-stage and the second-stage labor market are actually linked.

[15]When calculating the student-professor ratio, the MOE does not distinguish professors with domestic doctoral degrees from those obtained overseas degrees. Besides, there is no clear empirical evidence to link the ability of teaching to where an individual obtains his or her doctoral degree. Thus, here we assume each professor has the same ability to offer higher education.

The price of new knowledge produced at time t is π_t. The value of new knowledge is shared by the professor and his or her doctoral students. Professor has to pay a wage of s_t to each doctoral student involved in the knowledge production. Therefore, the surplus of knowledge production for a professor ($h_{\mathbb{I},t}$) is given by

$$h_{\mathbb{I},t} = \pi_t x_{\mathbb{I},t} - s_t m_{\mathbb{I},t}. \tag{1}$$

In addition to the surplus, professors also receive a wage of d_t, which is irrelevant to research and assumed to be exogenously given in the model. It will be discussed in the next subsection. The professor hires the optimal number of domestic doctoral students by maximizing (1). Thus, a domestic doctoral student is paid at his or her marginal product:

$$s_t = \pi_t \lambda \phi_x (m_{\mathbb{I},t})^{\theta_x - 1} (x_{\mathbb{I},t})^{1-\frac{\theta_x}{\lambda}}.$$

The above equation implies that professor with higher research efficiency will hire more (fewer) doctoral students if $\lambda > \theta_x$ (if $\lambda < \theta_x$). Moreover, the number of domestic doctoral students that a professor hires is decreasing in s_t. This implies that professor desires to have more doctoral students if s_t is lower. However, a lower s_t results in a lower incentive for young agents to enter domestic doctoral programs. Thus, the equilibrium s_t is determined by professor's demand as well as the supply of domestic doctoral students. We will further discuss an agent's occupational choice in Section 2.4.

Perfectly competitive firms in the industry sector employ accumulated knowledge and workers' efficient labor as inputs to produce final consumption goods. Since the number of professors at time t is $R_{\mathbb{I},t}$, the new knowledge produced in the academic sector is $x_{0,t}R_{0,t} + x_{1,t}R_{1,t}$. Moreover, we assume that knowledge depreciates at a rate of $\delta \in (0,1)$.[16] Thus, the law of motion of knowledge is given by

$$K_t = x_{0,t}R_{0,t} + x_{1,t}R_{1,t} + (1-\delta)K_{t-1}.$$

The supply of workers' efficient labor at time t is as follows:

$$\begin{aligned} L_t = & \sum_{j=t-4}^{t} n_j(1-\mu_j) + \sum_{j=t-4}^{t-1} n_j\left[(\mu_j - \varepsilon_j)(1-q_{0,j}) + \varepsilon_j(1-\zeta)(1-q_{1,j})\right] \\ & + \kappa \sum_{j=t-4}^{t-1} n_j\left[(\mu_j - \varepsilon_j)q_{0,j}(1-p_{0,j+1}) + \varepsilon_j(1-\zeta)q_{1,j}(1-\alpha p_{1,j+1})\right]), \end{aligned} \tag{2}$$

where $\kappa \geq 1$ is the labor efficiency of a Ph.D. worker. Equation (2) indicates that the labor supply of workers at time t consists of those who choose to be workers in the current and previous four generations, doctoral students who fail to graduate from Ph.D. programs in the previous four generations, and the number of Ph.D. workers in the previous four generations.

The industry sector employs knowledge and workers' effective labor to produce final consumption goods by a CES technology:

$$Y_t = A\left[(1-\phi_Y)K_t^{\theta_Y} + \phi_Y L_t^{\theta_Y}\right]^{1/\theta_Y}, \tag{3}$$

[16] The knowledge capital model is proposed by Griliches (1979) and has become the cornerstone of R&D literature. It is worth to note that, although knowledge does not depreciate in the way physical capital does, its value in producing final goods may become obsolete when new knowledge is discovered or when the environment changes over time. Therefore, knowledge depreciation is included in our model.

where $A > 0$ represents the total factor of productivity (TFP) and $\phi_Y \in (0,1)$ is the share parameter. The parameter θ_Y governs the elasticity of substitution between knowledge and labor inputs, where the elasticity is given by $1/(1-\theta_Y)$. The value of θ_Y is less than or equal to one and can be $-\infty$. We further denote $k_t = K_t/L_t$ and $y_t = Y_t/L_t$ as the knowledge-labor and the output-labor ratios, respectively. In equilibrium, the wage rate of worker's labor is equal to its marginal product. That is,

$$w_t = \phi_Y A \left[(1-\phi_Y)k_t^{\theta_Y} + \phi_Y\right]^{\frac{1-\theta_Y}{\theta_Y}}, \tag{4}$$

and Ph.D. workers' labor is paid at the rate of κw_t, where κ is the wage premium for Ph.D. workers. The gap between the industry sector's output and workers' total wages becomes the return of the new knowledge x_t and professor's wage d_t. As d_t is exogenously given in Taiwan, the price of knowledge (π_t) is determined by the market-clearing condition (hereafter the resource constraint) for final consumption goods at time t.[17] The resource constrain is given by

$$Y_t - w_t L_t = \pi_t (x_{0,t} R_{0,t} + x_{1,t} R_{1,t}) + d_t (R_{0,t} + R_{1,t}). \tag{5}$$

It is worth to note that L_t is measured in efficiency units in which κ is included. Thus, in (5), the total wages received by workers are $w_t L_t$. Equation (3) to (5) indicate that the accumulation of knowledge improves the labor productivity in the industry sector; however, professors and domestic doctoral students only obtain the value of new knowledge, $\pi_t(x_{0,t}R_{0,t} + x_{1,t}R_{1,t})$. Therefore, the labor productivity improved by the knowledge accumulated in the previous periods, $(1-\delta)K_{t-1}$, represents a spillover effect from the academic sector to the industry sector.

2.4 Occupational Choice

The preferences of agents of generation t who stay in the home country are represented by $\sum_{j=0}^{4} \beta^j \ln(c_{t+j})$, where c_t is the level of consumption, and $\beta \in (0,1)$ is the time preference discount factor. The level of consumption at period t is financed by an agent's income, including worker's wage (w_t or κw_t), financial compensation to doctoral students, the surplus in knowledge production ($h_{\mathbb{I},t}$), or professor's wage (d_t), depending on an agent's occupational choice. Since there is neither physical capital nor a financial market in our setting, all agents are hand-to-mouth and consume all of their income in each period of time.

[17] When constructing the model, we have the following three facts of Taiwan in mind. First, wages of professors who are at the same rank are almost the same. This implies that professor's wage is not endogenously determined. Second, there is no market to determine the value of research output. That is, the value of professor's research output is not decided by the market. Rather, the value of research output is determined by research grants, which are mostly funded by the government, such as the National Science and Technology Council. Third, the government's ability for financing research and professor's wage is limited by total tax revenues collected by the government. Since we do not introduce the government sector to the basic model, research grants and professor's wage are naturally limited by the resource constraint of the economy. Thus, when we set up the model, first of all, we assume professor's wage is exogenously given, as we impose $d_t = \bar{d}$ in Section 2.5. Then, the price of knowledge is not decided by its marginal product in (3). Instead, as professor's wage has been given and labor wage is determined by its marginal product, we are able to use the resource constraint (5) to decide the price of knowledge.

Specifically, the lifetime utility of being a worker for generation t is given by

$$W_t(i) = \ln(w_t) + \sum_{j=1}^{4} \beta^j \ln(w_{t+j}). \tag{6}$$

It is worth to note that workers do not join the knowledge production, but the accumulation of knowledge indeed affects workers through the marginal product of labor in (4). The expected lifetime utility of being a domestic doctoral student for generation t with caliber i becomes

$$\begin{aligned} D_t(i) = \ln(s_t) \ &+ f_t(i)\left[p_{t+1}\sum_{j=1}^{4}\beta^j \ln(d_{t+j}+h_{0t+j}) + (1-p_{t+1})\sum_{j=1}^{4}\beta^j \ln(\kappa w_{t+j})\right] \\ &+ \big(1-f_t(i)\big)\left[\sum_{j=1}^{4}\beta^j \ln(w_{t+j})\right]. \end{aligned} \tag{7}$$

That is, a domestic doctoral student will become a professor with the probability $f_t(i)p_{t+1}$, a Ph.D. worker with the probability $f_t(i)(1-p_{t+1})$, or a worker with the probability $1-f_t(i)$ in the old periods.

For an agent who studies abroad for an international doctoral degree, the preference is represented by

$$\sum_{j=0}^{4} \beta^j \ln(c_{t+j}) + v_1,$$

where v_1 represents the exogenous expected net gains from studying abroad compared to staying in the home country. In addition, if a young agent decides to be an international doctoral student, he or she earns a scholarship according to his or her caliber $f_t(i)$. Thus, the financial compensation to an international doctoral student i is the scholarship $\psi f_t(i)$, where $\psi > 0$ is a scaling parameter for the scholarship.[18] Then, the expected lifetime utility of being an international doctoral student for generation t with caliber i is

$$\begin{aligned} I_t(i) = \ln[\psi f_t(i)] + v_1 \ &+ f_t(i)\left[\alpha p_{t+1}\sum_{j=1}^{4}\beta^j \ln(d_{t+j}+h_{1t+j}) + (1-\alpha p_{t+1})\sum_{j=1}^{4}\beta^j \ln(\kappa w_{t+j})\right] \\ &+ \big(1-f_t(i)\big)\left[\sum_{j=1}^{4}\beta^j \ln(w_{t+j})\right]. \end{aligned} \tag{8}$$

Now we are ready to provide conditions for occupational choices. A young agent will decide to pursue a doctoral degree if the expected lifetime utility of being a doctoral student is at least as good as that of a worker. In other words, a young agent with caliber i of generation t will choose to be an international doctoral student if (8) $\geq$ (7) and (8) $\geq$ (6). He or she will choose to be a domestic doctoral student if (7) $>$ (8) and (7) $\geq$ (6). Otherwise, a young agent will become a worker.

[18] We assume that the wage of a domestic doctoral student is independent of the student's caliber, but the scholarship for studying abroad depends on $f_t(i)$. This assumption captures the fact that universities in the rest of the world usually provide various amounts of scholarships to attract international students.

2.5 Steady-State Equilibrium and Welfare

This subsection begins with a steady-state equilibrium for the model. Then, we define welfare for young agents with various occupational states. A professor's wage, d_t, is exogenous, so we assume $d_t = \bar{d}$. Moreover, $f_t(i)$ is specified as $f_t(i) = be^{-bi/n_t}$, an exponential function of the ratio i/n_t. Therefore, the ex ante distribution of caliber of each new agent does not change with the population size. This specification of $f_t(i)$ ensures that the proportion of students pursuing doctoral degrees μ_t converges to a steady-state equilibrium value μ^*. Similarly, the steady-state equilibrium values of ε_t, s_t, w_t, p_t, $q_{\mathbb{I},t}$, $m_{\mathbb{I},t}$, $x_{\mathbb{I},t}$, $h_{\mathbb{I},t}$, π_t, k_t, and y_t exist and are denoted by ε^*, s^*, w^*, p^*, $q_{\mathbb{I}}^*$, $m_{\mathbb{I}}^*$, $x_{\mathbb{I}}^*$, $h_{\mathbb{I}}^*$, π^*, k^*, and y^*, respectively. These steady-state values are determined as follows. First, the average graduation rates in the steady state for domestic and international doctoral students are pinned down by

$$q_0{}^* = \frac{e^{-b\varepsilon^*} - e^{-b\mu^*}}{\mu^* - \varepsilon^*}, \tag{9}$$

and

$$q_1{}^* = \frac{1 - e^{-b\varepsilon^*}}{\varepsilon^*}, \tag{10}$$

respectively. Thus, in the steady state, the market-clearing condition in the first-stage Ph.D. labor market becomes

$$m_0{}^*(\mu^* - \varepsilon^*)q_0{}^*p^* + m_1{}^*\varepsilon^*q_1{}^*(1-\zeta)\alpha p^* = \hat{g}(\mu^* - \varepsilon^*), \tag{11}$$

where $\hat{g} = g^4/\sum_{j=0}^{3} g^j$. Similarly, in the steady state, the market-clearing condition in the second-stage Ph.D. labor market becomes

$$p^* = \frac{\hat{g}}{a\left[(\mu^* - \varepsilon^*)q_0{}^* + \varepsilon^* q_1{}^*(1-\zeta)\alpha\right]}. \tag{12}$$

Second, the occupational-choice constraints determine the steady-state equilibrium proportions of ε^* and μ^*. A young agent with the caliber $i = \varepsilon^*$ is indifferent between being an international and a domestic doctoral student. The equilibrium condition derived from the occupational-choice constraint for ε^* is given by

$$\ln\Big(\frac{\psi b}{s^*}\Big) + v_1 = b\varepsilon^* - \hat{\beta} b e^{-b\varepsilon^*}\left[\alpha p^* \ln(\bar{d} + h_1{}^*) - p^* \ln(\bar{d} + h_0{}^*) - p^*(\alpha - 1)\ln(\kappa w^*)\right], \tag{13}$$

where $\hat{\beta} = \sum_{j=1}^{4} \beta^j$. In addition, a young agent with $i = \mu^*$ is indifferent between being a domestic doctoral student and a worker. The occupational-choice constraint determines the equilibrium value of μ^*:

$$\ln\left(\frac{s^*}{w^*}\right) = -\hat{\beta} b e^{-b\mu^*}\left[p^* \ln(\bar{d} + h_0{}^*) + \big(1 - p^*\big)\ln(\kappa w^*) - \ln w^*\right], \tag{14}$$

where $\hat{\beta} = \sum_{j=1}^{4} \beta^j$. Therefore, in equilibrium, young agents of $i \in [0, n_t\varepsilon^*]$ and $i \in (n_t\varepsilon^*, n_t\mu^*]$ will become international and domestic doctoral students, respectively.

Third, the proportions ε^* and μ^* along with $q_{\mathbb{I}}^*$ and p^* determine the equilibrium number of domestic doctoral students, professors, and workers, which are the inputs in the academic and the industry sectors. We then obtain the knowledge production for each professor

$$x_{\mathbb{I}}{}^* = \left[(1 - \phi_x)B_{\mathbb{I}} + \phi_x(m_{\mathbb{I}}{}^*)^{\theta_x}\right]^{\lambda/\theta_x}. \tag{15}$$

The output in the industry sector is given by

$$y^* = A\left[(1-\phi_Y)(k^*)^{\theta_Y} + \phi_Y\right]^{1/\theta_Y}, \tag{16}$$

where the equilibrium knowledge-labor ratio k^* is

$$k^* = \frac{gp^*}{g+\delta-1}\frac{(\mu^*-\varepsilon^*)q_0{}^*x_0{}^* + \varepsilon^* q_1{}^*(1-\zeta)\alpha x_1{}^*}{l^*}, \tag{17}$$

and l^* is defined as

$$l^* = (1-\mu^*)(1+\hat{g}) + (\mu^*-\varepsilon^*)\left[1-q_0{}^* + q_0{}^*(1-p^*)\kappa\right] + \varepsilon^*(1-\zeta)\left[1-q_1{}^* + q_1{}^*(1-\alpha p^*)\kappa\right].$$

Moreover, the steady-state resource constraint of (5) becomes[19]

$$y^* - w^* = \frac{(\mu^*-\varepsilon^*)q_0{}^*p^*(\pi^*x_0{}^* + \bar{d}) + \varepsilon^* q_1{}^*(1-\zeta)\alpha p^*(\pi^* x_1{}^* + \bar{d})}{l^*}. \tag{18}$$

The equilibrium number of domestic doctoral students hired by a professor is determined by

$$m_{\mathbb{I}}{}^* = \left(\frac{\pi^*\lambda\phi_x}{s^*}(x_{\mathbb{I}}{}^*)^{1-\frac{\theta_x}{\lambda}}\right)^{\frac{1}{1-\theta_x}}. \tag{19}$$

The wage for a worker is determined by his or her marginal product

$$w^* = \phi_Y A\left[(1-\phi_Y)(k^*)^{\theta_Y} + \phi_Y\right]^{\frac{1-\theta_Y}{\theta_Y}}. \tag{20}$$

Finally, the equilibrium surplus for a professor in the knowledge production is

$$h_{\mathbb{I}}{}^* = \pi^* x_{\mathbb{I}}{}^* - s^* m_{\mathbb{I}}{}^*,. \tag{21}$$

Equations (9) to (21) constitute the steady-state equilibrium in our model.

We further use average lifetime utility to measure the welfare for young agents with different occupational states. Recall that, in the steady-state equilibrium, young agents of $i \in [0, n_t\varepsilon^*]$, $i \in (n_t\varepsilon^*, n_t\mu^*]$, and $i \in (n_t\mu^*, n_t]$ will become international doctoral students, domestic doctoral students, and workers, respectively. Thus, the welfare of different occupational states are as follows:

$$\begin{aligned} U_D &\equiv \frac{\int_{n_t\varepsilon^*}^{n_t\mu^*} D_t(i)\,di}{n_t(\mu^*-\varepsilon^*)} \\ &= \ln s^* + \frac{e^{-b\varepsilon^*} - e^{-b\mu^*}}{\mu^*-\varepsilon^*}\left[p^*u_0 + \left(1-p^*\right)u_K - u_W\right] + u_W \end{aligned} \tag{22}$$

for domestic doctoral students,

$$\begin{aligned} U_I &\equiv \frac{\int_0^{n_t\varepsilon^*} I_t(i)\,di}{n_t\varepsilon^*} \\ &= \ln\psi + v_1 + \ln b - \frac{b\varepsilon^*}{2} + \frac{1-e^{-b\varepsilon^*}}{\varepsilon^*}\left[\alpha p^* u_1 + \left(1-\alpha p^*\right)u_K - u_W\right] + u_W \end{aligned} \tag{23}$$

[19]The derivations of k^* and $y^* - w^*$ are provided in Appendix B.

for international doctoral students, and

$$U_W \equiv \frac{\int_{n_t\mu^*}^{n_t} W_t(i)\,di}{n_t(1-\mu^*)} = \ln w^* + u_W \tag{24}$$

for workers, where $u_0 = \hat{\beta}\ln(\bar{d}+h_0{}^*)$, $u_1 = \hat{\beta}\ln(\bar{d}+h_1{}^*)$, $u_K = \hat{\beta}\ln\kappa w^*$, and $u_W = \hat{\beta}\ln w^*$.[20] The average lifetime utility of the whole population (hereafter, the average welfare) is

$$U \equiv \varepsilon^* U_I + (\mu^* - \varepsilon^*)U_D + (1-\mu^*)U_W. \tag{25}$$

We summarize the model equilibrium in the following proposition.

Proposition 1. *In steady state, the endogenous variables converge to their equilibrium values of* $q_{\mathbb{I}}^*$, $m_{\mathbb{I}}^*$, p^*, ε^*, μ^*, $x_{\mathbb{I}}^*$, y^*, π^*, k^*, s^*, w^*, *and* $h_{\mathbb{I}}^*$ *such that* (9)–(21) *are satisfied. Moreover, the welfare of domestic doctoral students, international doctoral students, workers, and the whole population is computed by* (22)–(25)*, respectively.*

Based on Proposition 1, we calibrate the model at steady state in the next section. Using the calibrated result as the benchmark economy, we conduct several policy experiments to study the effects of subsidies in Section 4.

3 Quantitative Analysis

In the benchmark economy, we calibrate the data from Taiwan to represent an economy with a productivity difference between obtaining a domestic and an international doctoral degree. There are two features of Taiwanese data. First, the basic wages for professors in Taiwan are publicly available and almost the same across colleges and fields. Therefore, the uncertainty of lifetime income for pursuing a doctoral degree is mainly due to the probability of graduation and the probability of finding an academic faculty position. Second, the supply of domestic doctoral graduates can be precisely estimated because most of them only search for local academic positions during the period we examine.

The calibration strategies are summarized in Section 3.1. Specifically, the calibration is conducted by field. This enables us to explore differentiated impacts across fields. Then, Section 3.2 discusses the calibrated results.

3.1 Parameterizations

The model is calibrated as a steady state to fit data from Taiwan during the period from 2006 to 2015. In particular, we calibrate the whole economy (denoted by "the aggregate" or "AGG") as well as the following five fields: engineering (ENG), science (SCI), medical sciences (MED), humanities (HUM), and social sciences (SOC).[21] Engineering includes engineering, manufacturing, and

[20] In (22), (23), and (24), n_t in the denominator and the numerator are cancelled out. Therefore, the welfare of different occupational states (U_D, U_I, and U_W) are stable and constant in the steady state.

[21] The aggregate is the summation of the five fields. Each field is separately calibrated.

construction; science refers to the field of science; medical sciences contains the fields of medical sciences, health, and social welfare; humanities includes humanities and the arts; and social sciences refers to social sciences, business, and law.[22] Table 1 reports the parameters. The data sources and detailed descriptions of the data are summarized in Appendix C.

There are eight common parameters, including T, β, δ, θ_Y, θ_x, λ, ψ, and ζ. First, T is the length of the model period. The first period in our model refers to the period before finding a faculty position. Thus, we set T as the number of years to complete a Ph.D. plus two years of postdoctoral experience. The average time to complete a Ph.D. in Taiwan was around 5.95 years (from 2006 to 2015). Therefore, T is set at 8 years ($8 = 6 + 2$) in the calibration. The second common parameter β is the time preference discount factor. We set the annual discount rate as 0.96, and hence the corresponding β in the model is 0.721. The third common parameter is the depreciation rate of knowledge. Following Doraszelski and Jaumandreu (2013), the annual depreciation rate of knowledge is set at 15%, and hence $\delta = 0.728$ in the calibration.[23] In the output production technology, θ_Y governs the elasticity of substitution between knowledge and labor inputs. We set $\theta_Y = 0.01$, so that the output production technology approximates a Cobb-Douglas function.[24] There are two common parameters in the knowledge production technology, θ_x and λ. Similar to θ_Y, the parameter θ_x governs the elasticity of substitution between a professor and his or her doctoral students in the knowledge production. We also set $\theta_x = 0.01$ to approximate a Cobb-Douglas function.[25] The parameter λ governs the degree of returns to scale in the knowledge production. To be symmetric to the output function, we assume $\lambda = 1$, which implies a constant-returns-to-scale technology. The rest two common parameters are related to international doctoral students. The first one, ψ, is a scaling parameter of scholarships for international doctoral students. We set $\psi = 3$.[26] The second one, ζ, refers to the ratio of brain drain, which is the percentage of international doctoral students who work in other countries and do not return to Taiwan after graduation. The National Center for Science and Engineering Statistics (NCSES) survey data reported that 16,155 doctorate recipients were temporary visa holders in the United States in 2015. Among them, 1,076 recipients had definite commitments to academic employment, and 2,070 recipients had industry employment in the United States. Therefore, the percentage of doctoral graduates staying in the United States was about 19%. However, Docquier and Rapoport (2012) point out that the brain drain rate is negatively correlated with the economic development of the home country. Adjusted by the intention that Ph.D. graduates want to stay and work in the United States, we thus set $\zeta = 15\%$.[27]

[22] We follow the field classification made by the Ministry of Education (MOE) in Taiwan to define the five fields. See Appendix C for more details.

[23] In Appendix E.2, we also set the annual depreciation rate to be 5% or 10% and re-calibrate the model. The results are quantitatively similar to the benchmark economy.

[24] See Appendix E.4 for further discussions.

[25] In practice, there may not be a strong complementarity between a professor and graduate students, as a professor has the capability to conduct independent research without relying on graduate students. Further discussions and robustness tests for the substitutability between professors and graduate students are relegated to Appendix E.3.

[26] The effect of changing ψ is absorbed by the net utility gain of studying internationally v_1. Thus, we choose to assume $\psi = 3$ and calibrate v_1.

[27] See Appendix E.5 for the discussion on the adjustment of intention. Besides, among the common parameters that we

Table 1: Parameters

Notation	Definition	AGG	ENG	SCI	MED	HUM	SOC	Source/Target
Common parameters								
T	length of model period	8.000	8.000	8.000	8.000	8.000	8.000	identified from data
β	time preference discount factor	0.721	0.721	0.721	0.721	0.721	0.721	annual discount rate=0.96
δ	depreciation rate of knowledge	0.728	0.728	0.728	0.728	0.728	0.728	annual depreciation rate=15%; Doraszelski and Jaumandreu (2013)
θ_Y	govern the elasticity of substitution between knowledge and labor	0.010	0.010	0.010	0.010	0.010	0.010	approximate a Cobb-Douglas function
θ_x	govern the elasticity of substitution between professor and Ph.D. student	0.010	0.010	0.010	0.010	0.010	0.010	approximate a Cobb-Douglas function
λ	govern the degree of return to scale in knowledge production	1.000	1.000	1.000	1.000	1.000	1.000	a constant-returns-to-scale technology
ψ	scaling parameter for scholarships	3.000	3.000	3.000	3.000	3.000	3.000	preset
ζ	the ratio of brain drain	0.150	0.150	0.150	0.150	0.150	0.150	identified from data
Parameters by fields								
b	parameter governing graduation rates	0.763	0.833	0.777	0.754	0.657	0.691	calibrated to match q_0^*
α	job-market advantage for international Ph.D. graduates	1.169	1.247	1.309	1.204	1.091	1.019	identified from data
v_1	net utility gain of studying abroad	0.109	-0.135	-0.051	0.242	0.084	-0.340	calibrated to match ε^*
a	student-professor ratio	32.487	30.825	26.831	25.079	34.138	41.438	identified from data
g	gross growth rate of generation	0.999	0.919	0.938	1.007	1.225	0.981	identified from data
$\bar{d}$	professor wage	9.585	9.585	9.585	9.585	9.585	9.585	identified from data
ϕ_x	weight of Ph.D. students in knowledge production	0.144	0.015	0.034	0.081	0.895	0.030	calibrated to match s^*
B_0	productivity of professor with domestic degree	1.034	1.032	1.029	1.031	1.225	1.024	calibrated to match x_0^*
B_1	productivity of professor with international degree	1.037	1.036	1.032	1.032	1.227	1.028	calibrated to match x_1^*
ϕ_Y	weight of labor in output production	0.970	0.841	0.910	0.931	0.978	0.965	ϕ_Y and A are jointly calibrated to match w^* and μ^*
A	TFP in output function	5.606	9.010	7.421	6.906	4.768	5.786	ϕ_Y and A are jointly calibrated to match w^* and μ^*
κ	wage premium for Ph.D. worker	1.038	1.038	1.031	1.014	1.016	1.014	identified from data

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively.

There are twelve field parameters. First, the parameter b governs the graduation rates. Thus, b is calibrated to match the domestic graduation rate q_0^*. The data of the domestic graduation rate by field is calculated based on the number of doctoral students obtained from the MOE. As shown in Table 1, b is lower in humanities and social sciences, reflecting lower domestic graduation rates in these two fields. Second, two field parameters are related to international doctoral students, α and v_1. Recall that α represents the international doctoral graduate's advantage of finding faculty positions in the domestic Ph.D. labor market. Using the survey data conducted by the NPHRST, we distinguish professors with international degrees from those graduated domestically. We then calculate the ratio of the number of professors with international degrees to those who graduated domestically to obtain α in each field. The parameter v_1 captures the expected net utility of studying and working internationally. A positive v_1 represents an expected utility gain of studying and working internationally. A negative v_1 implies an expected utility loss. With the international student's occupational-choice constraint (13), we calibrate v_1 to match the proportion of a generation who decide to study abroad in the data. The details of the target are discussed in Appendix C.

Third, there are three parameters related to an academic faculty position, g, a, and $\bar{d}$. The parameter g denotes the gross rate of generation growth, which is defined as the total number of undergraduate and master's students. Using the data from the MOE, we compute the annual gross rate of generation growth. Then, the annual rate is converted by the length of the model period to obtain g. As reported in Table 1, the gross rates of generation growth in most fields are less than one, implying that the total number of undergraduates and master's students is decreasing, except in medical sciences and humanities. Nevertheless, with a low birth rate in Taiwan, the gross generation growth rates in all fields are expected to be even lower in the near future.[28] As undergraduates and master's students are potential doctoral students, the low birth rate in Taiwan motivates us to conduct policy experiments to bridge the talent gap in higher education in the next section. In addition, we use the stocks of students and professors at all ranks in the MOE data to compute the student-professor ratio a. The details are described in Appendix C. Finally, $\bar{d}$ is the exogenous professor's wage. In Taiwan, professors' wages are publicly available and are almost the same in a rank. The average annual salary is about 1.05 million, 1.18 million, and 1.36 million New Taiwan Dollars (TWD) for assistant professors, associate professors, and full professors, respectively. We assume that, during one's academic career, the lengths of being an assistant, an associate, and a full professor are all equal. Adjusting the average professor wage by the length of the model period, we obtain the professors' wage ($\bar{d}$) of 9.585 million TWD.

The fourth group is the parameters in knowledge production: ϕ_x, B_0, and B_1. Note that ϕ_x is the weight of doctoral students in knowledge production. It is calibrated to match the wage of a doctoral student (s^*). The data of the wage of a doctoral student are obtained through a survey conducted

report in the first panel of Table 1, one particularly significant and intriguing parameter that can vary across fields is the ratio of brain drain. Therefore, we conduct a quantitative analysis for varying ζ in Appendix E.5.

[28] The rapid decline in population entering undergraduates become obvious after 2015. This implies that the gross growth rate of generation after the data period that we study would be even lower. To examine the effect of a lower generation growth rate on our quantitative analysis, we re-calculate g by the MOE data from 2006 to 2022 for every field, while other data moments and targets remain unchanged. The results are summarized in Appendix E.1.

by the Graduate Student Association of National Taiwan University (NTU). We first calculate the yearly income of a domestic doctoral student in each field.[29] Second, in Taiwan, it is common to have two years of postdoctoral experience for Ph.D. graduates in engineering, science, and medical sciences. In contrast, although obtaining a Ph.D. degree in humanities and social sciences takes longer, postdoctoral experience is not required for finding an academic faculty position. Therefore, in the aggregate and in the fields of engineering, science, and medical sciences, the targeted wage of a doctoral student includes six years of a doctoral student's income and two years of postdoctoral salary. In humanities and social sciences, the targeted wage of a doctoral student is simply the eight years of a doctoral student's income. The parameter B_0 denotes the productivity in knowledge production of professors with domestic degrees, and B_1 is that of professors with international degrees. They are calibrated to match knowledge output x_0^* and x_1^*, respectively. We use Ministry of Science and Technology (MOST) research grants in Taiwan to approximate a professor's knowledge output. The details are provided in Appendix C. As shown in Table 1, the productivity of a professor with an international degree on average is higher than that of his or her counterparts in all fields ($B_1 > B_0$). However, the productivity differential (measured by B_0/B_1) differs among fields. It is 0.997, 0.996, 0.997, 0.999, 0.998, and 0.997 for the aggregate, engineering, science, medical sciences, humanities, and social science, respectively. The largest gap exists in engineering, while the smallest is in medical sciences. As we will discuss in Section 5, the size of the productivity gap plays an important role in the effect of subsidy policies.

The remaining three parameters (κ, ϕ_Y, and A) are related to workers and the industry sector. The parameter κ refers to the wage premium of a Ph.D. worker. It is measured by the ratio of the average wage of a worker with a doctoral degree to that without a doctoral degree. We use the data from the MOE and the Ministry of Labor (MOL) in Taiwan to calculate κ. The wage premium ranges from 1.4% to 3.8% among fields, and the values in engineering and science are higher than those in other fields, reflecting higher market values of Ph.D. training and subsequent R&D activities in the industries for these two fields. Because the wage of a professor in Taiwan is almost the same, the higher wage premium in engineering and science reflects that, in addition to academic careers, doctoral graduates in these fields have relatively higher incentives to be employed in high-tech companies. Moreover, ϕ_Y and A are the weights of labor and TFP in the industry sector, respectively. They are jointly calibrated to match μ^* and w^*. The first target μ^* denotes the proportion of a generation who decide to be doctoral students. By definition, it is the sum of the proportion of the generation who study abroad and the proportion who decide to be domestic doctoral students. As described in Appendix C, these proportions are calculated using the MOE data. The second target is workers' wages in the output sector (w^*). It is computed as follows. For each field, we first calculate the average monthly wage for a full-time job. Second, the average monthly wage for a full-time job is adjusted by the percentage of having a full-time job to obtain the expected monthly wage. Third, a

[29] We use a 12-month salary as a domestic doctoral student's yearly income, as it is common to have a 12-month part-time research assistant position in Taiwan. Also, it is rare for a part-time research assistant to have an annual bonus in Taiwan, so an annual bonus is not included here. The wage of a domestic doctoral student in the aggregate is the weighted average of the five fields we conduct, where the weight is the percentage of domestic doctoral students in the corresponding field.

yearly bonus (which equals 1.5 months of salary in all fields) is included to have the expected yearly income for a full-time job.[30] Finally, the expected yearly wage is adjusted by the length of the model period to obtain the target value.

3.2 Benchmark Economy

Table 2 summarizes the calibrated results for all fields. Parameters in Table 1 and calibrated results in Table 2 constitute the benchmark economy for our experiments in later sections. There are several observations in the calibrated result. First, engineering, science, and medical sciences have higher average graduation rates (q_0^* and q_1^*) but lower chances of finding faculty positions (p^*). This is because the proportion of the generation who choose to be doctoral students is larger in these fields. As a result, having many Ph.D. graduates leads to lower chances of finding a faculty position.

Second, a worker's wage in the industry (w^*) is higher in engineering, science, and medical sciences than in humanities and social sciences. As studying in a doctoral program is an endogenous decision, the higher worker's wage implies that students in these three fields expect to earn larger surpluses in knowledge production when they become professors.[31] This argument is supported by the larger surpluses in knowledge production (h_0^* and h_1^*) for the three fields in Table 2.[32] Moreover, we also observe more domestic doctoral students per professor (m_0^* and m_1^*) in the three fields. More domestic doctoral students result in higher knowledge stock (k^*) and, therefore higher output per labor (y^*).

Third, x_0^* and x_1^* are knowledge outputs per professor with a domestic Ph.D. degree and an international degree, respectively. They are our targets to calibrate the productivity of professors B_0 and B_1. Because productivity is not observable, we use MOST research grants as proxies for the two targets. As shown in Table 2, x_1^* is larger than x_0^* in all fields. Therefore, our benchmark economy represents the existence of a productivity differential such that $B_1 > B_0$ in all fields.

Moreover, by comparing different fields, we find that the role of domestic doctoral students in knowledge production and knowledge accumulation is important. Having more domestic doctoral students results in more knowledge production and, therefore higher output per labor. The main mechanism is that the accumulation of knowledge contributes to labor productivity in the output sector and then raises the output as well as the average welfare, i.e., the spillover effect. In the following analysis, we will conduct experiments to study this mechanism. Nevertheless, the size of the productivity differential in knowledge production is crucial to the impact of the spillover effect. If the size of the productivity differential is large enough, the spillover effect could be dominated by the influence of the productivity differential. We will further discuss this issue in Sections 4 and 5.

[30] The actual yearly bonuses vary across industries. However, because the bonus data are not available, we adopt 1.5 months of salary that Taiwanese civil servants usually obtain as the representative bonus.

[31] In our model, an agent compares the expected lifetime utility of a professor to that of a worker. Because $s^* < w^*$ and professor wage $\bar{d}$ is fixed and equal in all fields, to satisfy the occupational-choice constraint, it must be the case that he or she expects larger surpluses in knowledge production.

[32] Besides, the value of π^* is larger in engineering and science than in medical sciences, consistent with the higher market value of Ph.D. training and R&D in the industry (κ) in these two fields.

Table 2: The benchmark economy

Variable	AGG		ENG		SCI		MED		HUM		SOC		Target/Method
	model	data	model	data	model	data	model	data	model	data	model	data	
Calibrated result													
ε^*	0.017	0.017	0.024	0.024	0.023	0.023	0.028	0.028	0.012	0.012	0.008	0.008	target for calibration
μ^*	0.039	0.039	0.056	0.056	0.055	0.055	0.068	0.068	0.028	0.028	0.020	0.020	target for calibration
q_0^*	0.748	0.748	0.806	0.806	0.754	0.754	0.727	0.727	0.649	0.649	0.684	0.684	target for calibration
q_1^*	0.758	-	0.825	-	0.770	-	0.746	-	0.655	-	0.689	-	solved by q_1^* equation
m_0^*	0.655	-	0.813	-	0.735	-	0.962	-	0.499	-	0.420	-	solved by m_0^* equation
m_1^*	0.869	-	1.247	-	0.992	-	1.028	-	0.615	-	0.589	-	solved by the market clearing condition for total m^*
p^*	0.259	-	0.140	-	0.182	-	0.201	-	0.682	-	0.440	-	solved by p^* equation
s^*	2.952	2.952	2.842	2.842	2.916	2.916	3.229	3.229	2.266	2.266	1.733	1.733	target for calibration
h_0^*	11.936	-	152.158	-	62.296	-	36.459	-	0.164	-	24.344	-	solved by h_0^* equation
h_1^*	15.827	-	233.424	-	84.065	-	38.975	-	0.202	-	34.092	-	solved by h_1^* equation
x_0^*	16.463	16.463	22.098	22.098	15.444	15.444	16.800	16.800	5.651	5.651	10.093	10.093	target for calibration
x_1^*	21.830	21.830	33.901	33.901	20.841	20.841	17.960	17.960	6.963	6.963	14.134	14.134	target for calibration
w^*	5.147	5.147	5.959	5.959	5.767	5.767	5.765	5.765	4.408	4.408	5.112	5.112	target for calibration
k^*	0.161	-	0.215	-	0.168	-	0.197	-	0.068	-	0.076	-	solved by k^* equation
π^*	0.843	-	6.990	-	4.173	-	2.355	-	0.229	-	2.484	-	solved by domestic occupational-choice constraint
y^*	5.305	-	7.067	-	6.327	-	6.183	-	4.503	-	5.292	-	solved by the resource constraint
Average lifetime utility													
U	4.732	-	5.156	-	5.061	-	5.061	-	4.285	-	4.712	-	solved by U equation
U_I	4.753	-	5.195	-	5.095	-	5.096	-	4.298	-	4.728	-	solved by U_I equation
U_D	4.737	-	5.165	-	5.069	-	5.068	-	4.288	-	4.717	-	solved by U_D equation
U_W	4.732	-	5.155	-	5.060	-	5.059	-	4.284	-	4.712	-	solved by U_W equation

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively.

4 Policy Experiments

As mentioned in the introduction, there are serious concerns about the talent gap in Taiwan's higher education. Policy reforms to bridge the gap have been widely discussed. In practice, many countries provide subsidies to domestic doctoral students, such as Norway, Sweden, Taiwan, and the UK. On the other hand, subsidy policies to professors through research grants are also commonly adopted. Therefore, we conduct experiments for the two policy reforms and study the effects of the policy reforms on the economy. Both subsidies are financed by a flat income tax. The two occupational-choice constraints and the resource constraint are also modified accordingly. The experiments are solved as steady states and are compared with the benchmark economy. The details are provided in Appendix D.

4.1 Subsidy to Domestic Doctoral Students

Consider a policy reform in which each domestic doctoral student is subsidized by a fixed amount of student wage $\bar{s}$. The subsidy is financed by a flat income tax on every individual in the domestic economy. Given a tax rate τ, the total revenues collected are used to finance the subsidy. Therefore, in the steady state, $\bar{s}$ is determined as follows:

$$\bar{s} = \frac{\tau y^* l^*}{{m_0}^*(\mu^* - \varepsilon^*){q_0}^* p^* + {m_1}^* \varepsilon^* {q_1}^* (1-\zeta)\alpha p^*}. \tag{26}$$

In other words, the subsidy is a fraction of the total output y^*. Besides, under the policy reform, the equilibrium conditions derived from the occupational-choice constraints are also modified accordingly. Specifically, equation (13) becomes

$$\ln\left(\frac{\psi b}{s^* + \bar{s}}\right) + v_1 - \ln(1-\tau) = b\varepsilon^* - \hat{\beta} b e^{-b\varepsilon^*}\left[\alpha p^* \ln(\bar{d} + {h_1}^*) - p^* \ln(\bar{d} + {h_0}^*) - p^*(\alpha - 1)\ln(\kappa w^*)\right] \tag{27}$$

and equation (14) is replaced by

$$\ln\left(\frac{s^* + \bar{s}}{w^*}\right) = -\hat{\beta} b e^{-b\mu^*}\left[p^* \ln(\bar{d} + {h_0}^*) + (1-p^*)\ln(\kappa w^*) - \ln w^*\right]. \tag{28}$$

The resource constraint (18) becomes:

$$(1-\tau)y^* - w^* = \frac{(\mu^* - \varepsilon^*){q_0}^* p^*(\pi^* {x_0}^* + \bar{d}) + \varepsilon^* {q_1}^* (1-\zeta)\alpha p^*(\pi^* {x_1}^* + \bar{d})}{l^*}. \tag{29}$$

Other steady-state equilibrium equations remain unchanged. Finally, the welfare for domestic doctoral students is modified as:

$$\begin{aligned} U_D &= \ln(s^* + \bar{s}) + \frac{e^{-b\varepsilon^*} - e^{-b\mu^*}}{\mu^* - \varepsilon^*}\left[p^* u_0 + (1-p^*)u_K - u_W\right] + u_W \\ &\quad + (1+\hat{\beta})\ln(1-\tau), \end{aligned} \tag{30}$$

where $u_0 = \hat{\beta}\ln(\bar{d}+h_0{}^*)$, $u_K = \hat{\beta}\ln\kappa w^*$, $u_W = \hat{\beta}\ln w^*$, and $\hat{\beta} = \sum_{j=1}^{4}\beta^j$. The welfare of international doctoral students becomes:

$$\begin{aligned} U_I \; &= \ln\psi + v_1 + \ln b - \frac{b\varepsilon^*}{2} + \frac{1-e^{-b\varepsilon^*}}{\varepsilon^*}\left[\alpha p^* u_1 + \left(1-\alpha p^*\right)u_K - u_W\right] + u_W \\ &\quad + \hat{\beta}\ln(1-\tau), \end{aligned} \tag{31}$$

where $u_1 = \hat{\beta}\ln(\bar{d}+h_1{}^*)$. The welfare of workers is replaced by:

$$U_W = \ln w^* + u_W + (1+\hat{\beta})\ln(1-\tau). \tag{32}$$

In the quantitative experiment, we consider two scenarios: a tax rate of 0.05% and a tax rate of 0.1%. Table 3 summarizes the results. The first two rows in Table 3 report the values of equilibrium domestic doctoral students' wage s^* and the subsidy received by a domestic doctoral student $\bar{s}$. Others are percentage changes relative to the benchmark economy.

In the scenario of $\tau = 0.05\%$, the subsidy to domestic doctoral students brings two opposite effects to the accumulation of knowledge. On the one hand, compared to the benchmark economy, the policy reform results in a lower equilibrium wage for domestic doctoral students (s^*). However, the total financial compensation a domestic doctoral student receives becomes larger (the percentage changes of $s^* + \bar{s}$ relative to the benchmark economy are positive in all fields). The larger financial compensation attracts more entrants to study in domestic doctoral programs, and the number of students per professor (m_0^* and m_1^*) increases, thereby increasing the accumulation of knowledge (k^*). On the other hand, the increment of entrants comes from two sources: those who would be workers and those who would study abroad if there were no subsidies to domestic doctoral students. We find that the policy reform attracts students to stay in Taiwan, and reduces the number of students who study internationally (ε^*), and the share of professors who have international doctoral degrees. Because professors with overseas training have higher productivity in knowledge production ($B_1 > B_0$), the decline in the share of professors who have international degrees has a negative impact on knowledge accumulation. Therefore, the net impact of the policy reform on knowledge accumulation depends on the magnitudes of the aforementioned two opposite effects, and the productivity differential (B_0/B_1) plays an important role. Because the productivity gaps in medical sciences and humanities are smaller than those in other fields, as in Table 3, these two fields have a smaller decline in ε^*, and the accumulation of knowledge rises under the policy reform (k^* increases by 0.38% and 2.92% for medical sciences and humanities, respectively). Therefore, output per labor (y^*) in the two fields increases. In contrast, because of lower ε^* and larger productivity differentials, knowledge accumulations and output per labor in the aggregate and in engineering, science, and social sciences all decline. We find similar results in the scenario with $\tau = 0.1\%$.

To see the interaction of the aforementioned effects clearly, we depict the impacts of the subsidy on students' occupational choices, incentives for them, and the knowledge accumulation with various tax rates in Figure 1. The tax rate on the x-axis ranges from 0% to 0.1%, and the y-axis is the percentage change of the variable relative to the benchmark economy. The bottom-left figure shows that this subsidy increases the share of students who choose to enter domestic Ph.D. programs in all

Table 3: Impacts of subsidy to domestic doctoral students

	τ=0.05%						τ=0.1%					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
Wage of domestic doctoral student												
s^*	2.469	2.326	2.453	2.898	1.802	1.034	2.109	1.968	2.114	2.626	1.368	0.844
$\bar{s}$	0.490	0.522	0.472	0.340	0.464	0.705	0.859	0.885	0.818	0.622	0.899	1.172
Percentage change relative to the benchmark economy												
ε^*	-21.68%	-22.13%	-19.44%	-13.86%	-6.06%	-90.48%	-43.06%	-43.83%	-38.44%	-27.19%	-12.56%	-100.00%
$\mu^* - \varepsilon^*$	16.57%	21.19%	18.13%	10.64%	3.44%	64.45%	32.92%	42.07%	36.10%	21.15%	6.88%	97.69%
μ^*	0.51%	3.03%	2.38%	0.37%	-0.54%	-0.50%	1.01%	6.06%	4.85%	0.88%	-1.27%	14.87%
q_0^*	0.13%	0.15%	0.12%	0.14%	0.03%	0.27%	0.26%	0.29%	0.24%	0.27%	0.06%	0.19%
q_1^*	0.14%	0.22%	0.17%	0.15%	0.02%	0.26%	0.27%	0.43%	0.34%	0.29%	0.05%	0.29%
m_0^*	19.75%	26.92%	21.49%	11.08%	3.95%	87.24%	40.30%	55.72%	43.91%	22.11%	7.96%	128.23%
m_1^*	19.75%	26.92%	21.49%	11.08%	3.94%	87.24%	40.30%	55.72%	43.91%	22.11%	7.96%	128.23%
p^*	-0.56%	-2.28%	-1.32%	-0.22%	0.37%	-4.67%	-1.11%	-4.47%	-2.71%	-0.58%	0.91%	-17.78%
$s^* + \bar{s}$	0.24%	0.22%	0.28%	0.27%	0.03%	0.35%	0.56%	0.37%	0.54%	0.59%	0.05%	16.32%
h_0^*	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%	-0.10%	7.35%	3.95%	-0.89%	-34.87%	10.20%
h_1^*	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%	-0.10%	7.35%	3.95%	-0.89%	-34.87%	10.20%
x_0^*	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%	4.84%	0.67%	1.22%	1.58%	6.92%	2.44%
x_1^*	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%	4.84%	0.67%	1.22%	1.58%	6.92%	2.44%
w^*	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%	-0.02%	-1.32%	-0.39%	0.05%	0.12%	-0.40%
k^*	-0.22%	-4.21%	-2.17%	0.38%	2.92%	-10.64%	-0.76%	-8.23%	-4.34%	0.69%	5.82%	-11.31%
π^*	-2.47%	3.28%	1.33%	-1.24%	-20.07%	9.04%	-4.67%	6.64%	2.71%	-2.42%	-39.04%	7.61%
y^*	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%	-0.02%	-1.34%	-0.39%	0.05%	0.12%	-0.41%
Average lifetime utilities												
U	-0.04%	-0.40%	-0.14%	-0.02%	0.01%	-0.26%	-0.08%	-0.80%	-0.28%	-0.03%	0.01%	-0.31%
U_I	-0.05%	-0.40%	-0.14%	-0.01%	-0.02%	-0.26%	-0.11%	-0.80%	-0.30%	-0.05%	-0.00%	-
U_D	-0.03%	-0.35%	-0.10%	0.01%	-0.01%	-0.18%	-0.04%	-0.72%	-0.22%	0.00%	0.01%	-0.27%
U_W	-0.03%	-0.40%	-0.14%	-0.01%	0.01%	-0.26%	-0.07%	-0.80%	-0.28%	-0.03%	0.01%	-0.31%

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. In the scenario of $\tau = 0.1\%$, the change in ε^* in social sciences is -100.00%, which means $\varepsilon^* = 0$ in the experiment (a corner solution), and hence we do not report the change of U_I.

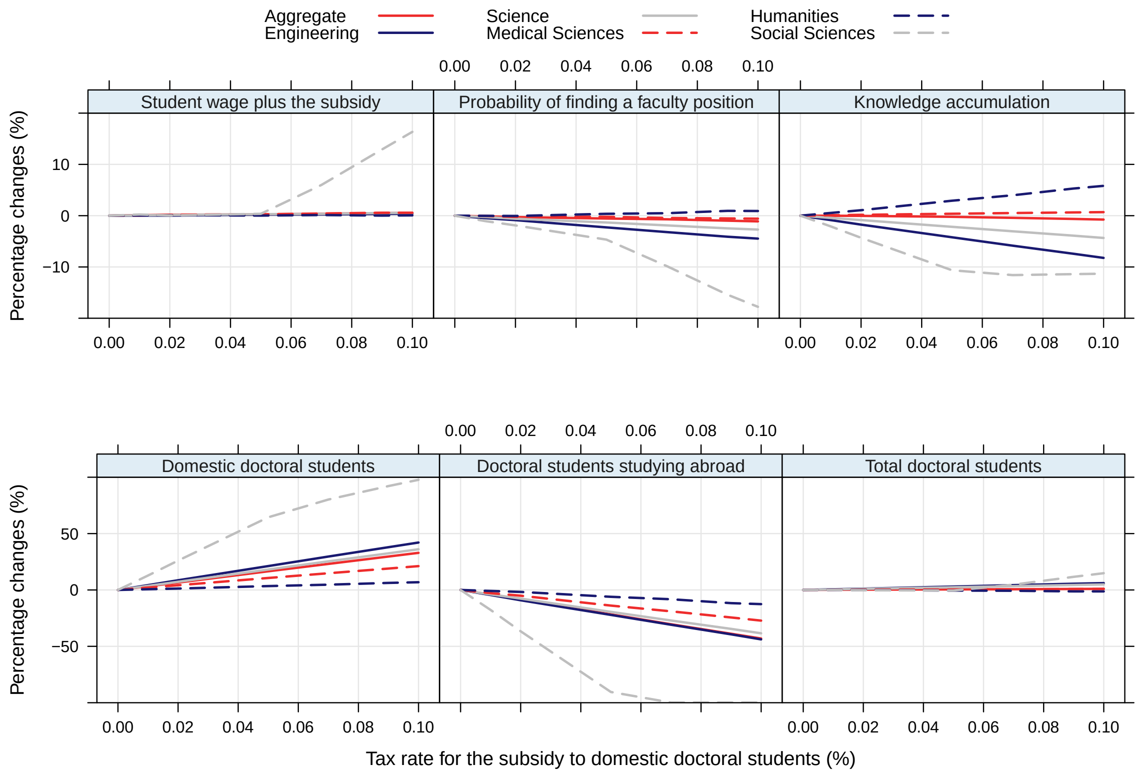

Figure 1: Subsidy to domestic doctoral students with various tax rates

fields, while it decreases the share of students who choose to enter foreign Ph.D. programs in all fields. Therefore, under the subsidy, we have more domestic doctoral students as inputs in knowledge production, but fewer professors from overseas training. Since the productivity differential between overseas and domestic training is smaller in medical sciences and humanities, the gains from having more domestic doctoral students as inputs in knowledge production dominate the losses from professors' productivity differential, and hence the knowledge accumulation in these two fields are increasing in τ. In contrast, the results of the rest fields suggest that the knowledge accumulation is weakly decreasing in τ.

In addition, the last four rows in Table 3 report changes in the welfare of the whole population (U), those who pursue international degrees (U_I), those who have domestic doctoral degrees (U_D), and those who are workers (U_W). The result suggests that most people are worse off under the policy reform due to lower knowledge accumulation, smaller output per labor, and the increase in tax. However, in the field of humanities, the effect of the increase in knowledge accumulation and output per labor dominates the impact of the increase in tax rate. Thus, workers in humanities are better off under the policy reform.[33] We conclude that the productivity differential matters for the effect of subsidy reform. To further study the role of productivity differential, we provide counterfactual

[33]Under the policy reform, domestic doctoral students in medical sciences also enjoy a slight welfare improvement. This is because they enjoy higher financial compensation ($s^* + \bar{s}$) and are only slightly hurt by the decline in professor surplus.

analysis in Section 5. Before that, in the next subsection, we study another popular policy: a subsidy to professors' research.

4.2 Subsidy to Professors' Research

Now we turn to consider a policy reform that is aiming at subsidizing professors. The policy reform provides a subsidy $\bar{\rho}_h$, which is proportional to a professor's research surplus.[34] Recall that the equilibrium research surplus for a professor in knowledge production is described in (21). Under the policy reform, a professor receives a subsidy of $\bar{\rho}_h h_0^*$ or $\bar{\rho}_h h_1^*$ in equilibrium. The subsidy is financed by a flat income tax rate τ. Thus, in steady state, the proportion of subsidy $\bar{\rho}_h$ is determined by

$$\bar{\rho}_h = \frac{\tau y^* l^*}{h_0{}^*(\mu^* - \varepsilon^*) q_0{}^* p^* + h_1{}^* \varepsilon^* q_1{}^* (1-\zeta)\alpha p^*}. \tag{33}$$

In addition, equation (13) becomes

$$\begin{aligned} \ln\Big(\frac{\psi b}{s^*}\Big) + v_1 - \ln(1-\tau) \quad &= \quad b\varepsilon^* - \hat{\beta} b e^{-b\varepsilon^*}\big[\alpha p^* \ln(\bar{d} + (1+\bar{\rho}_h)h_1{}^*) \\ &\quad - p^* \ln(\bar{d} + (1+\bar{\rho}_h)h_0{}^*) - p^*(\alpha - 1)\ln(\kappa w^*)\big], \end{aligned} \tag{34}$$

and equation (14) is replaced by:

$$\ln\left(\frac{s^*}{w^*}\right) = -\hat{\beta} b e^{-b\mu^*}\big[p^* \ln(\bar{d} + (1+\bar{\rho}_h)h_0{}^*) + \big(1-p^*\big)\ln(\kappa w^*) - \ln w^*\big]. \tag{35}$$

The resource constraint (18) is modified to be

$$(1-\tau)y^* - w^* = \frac{(\mu^* - \varepsilon^*) q_0{}^* p^* (\pi^* x_0{}^* + \bar{d}) + \varepsilon^* q_1{}^* (1-\zeta)\alpha p^* (\pi^* x_1{}^* + \bar{d})}{l^*}. \tag{36}$$

Other steady-state equations remain unchanged. The welfare for domestic doctoral students is given by:

$$\begin{aligned} U_D \ &= \ln s^* + \frac{e^{-b\varepsilon^*} - e^{-b\mu^*}}{\mu^* - \varepsilon^*}\left[p^* u_0^h + \big(1-p^*\big)u_K - u_W\right] + u_W \\ &\quad + (1+\hat{\beta})\ln(1-\tau), \end{aligned} \tag{37}$$

where $u_0^h = \hat{\beta}\ln(\bar{d} + (1+\bar{\rho}_h)h_0{}^*)$, $u_K = \hat{\beta}\ln\kappa w^*$, and $u_W = \hat{\beta}\ln w^*$. The welfare of students who pursue international doctoral degrees is

$$\begin{aligned} U_I \ &= \ln\psi + v_1 + \ln b - \frac{b\varepsilon^*}{2} + \frac{1 - e^{-b\varepsilon^*}}{\varepsilon^*}\left[\alpha p^* u_1^h + \big(1 - \alpha p^*\big)u_K - u_W\right] + u_W \\ &\quad + \hat{\beta}\ln(1-\tau), \end{aligned} \tag{38}$$

where $u_1^h = \hat{\beta}\ln(\bar{d} + (1+\bar{\rho}_h)h_1{}^*)$. The welfare for being workers after college graduation becomes:

$$U_W = \ln w^* + u_W + (1+\hat{\beta})\ln(1-\tau). \tag{39}$$

[34] We also examine an alternative policy of subsidizing professor's wage, and the finding is qualitatively similar to a subsidy to professors' research. For further information, please refer to Appendix D.3.

Similar to the policy that subsidizes domestic doctoral students, we consider two scenarios for the quantitative analysis: $\tau = 0.05\%$ and $\tau = 0.1\%$. The results are summarized in Table 4. The first two rows in Table 4 provide the amount of subsidy received by a professor in equilibrium. Others are percentage changes relative to the benchmark economy.

Because of the productivity differential, the subsidy provides more incentives to study overseas. As shown in Table 4, the proportion of studying overseas (ε^*) increases, but the proportion of entering domestic doctoral programs ($\mu^* - \varepsilon^*$) decreases in every field. Thus, domestic doctoral students per professor (m_0^* and m_1^*) decline, and knowledge outputs (x_0^* and x_1^*) are lower. In the aggregate and the fields of engineering, science, and social sciences, the result further suggests that the policy reform raises the accumulation of knowledge (k^*), although knowledge output decreases. This is because more students choose to study overseas rather than enter domestic programs under the policy reform. In (11), $\mu^* - \varepsilon^*$ decreases but ε^* increases. As the productivity differential exists, those who change their decisions from studying domestically to overseas will have higher productivity in knowledge production when they become professors, resulting in more knowledge accumulation. In contrast, as the productivity gaps in medical sciences and humanities are relatively small, the effect of switching from domestic programs to overseas on knowledge accumulation is minor. Thus, less knowledge output directly results in lower knowledge accumulation.

It is worth noting that the policy reform aims at subsidizing professors' research but eventually results in less "post-subsidy" research surplus, $(1+\bar{\rho}_h)h_0^*$ and $(1+\bar{\rho}_h)h_1^*$, in some fields. This is mainly due to fewer domestic doctoral students as inputs in knowledge production and, thereby lowering knowledge output when the policy is implemented. In contrast, in medical sciences and humanities, the decline in h_0^* and h_1^* is compensated by the larger amount of subsidies ($\bar{\rho}_h h_0^*$ and $\bar{\rho}_h h_1^*$).[35] Therefore, the "post-subsidy" research surplus received by professors in these two fields goes up.

The welfare changes reported in Table 4 show that most individuals are worse off under this policy reform. Only those in humanities and studying abroad enjoy welfare improvement (0.02%). This is mainly due to the significant increase in the "post-subsidy" research surplus received by professors. In contrast, although domestic doctoral students in humanities also enjoy a large "post-subsidy" research surplus when they become faculty, the student wage they receive during their Ph.D. studies is lower (-1.28%). Therefore, they have welfare loss due to the policy reform.

Comparing the two subsidies, we conclude that the subsidy to domestic doctoral students is more efficient in boosting the number of domestic doctoral students. However, we also find that increasing in domestic doctoral students does not imply more knowledge accumulation. If the productivity differential is not large, increases in domestic doctoral students can lead to more knowledge accumulation, such as in medical sciences and humanities in Table 3. Otherwise, the number of domestic doctoral students and knowledge accumulation move in the opposite direction. Thus, in the fields with relatively large productivity differentials, a subsidy to professors' research slightly increases knowledge accumulation, while lowering the incentives to enter domestic doctoral programs.

[35] For example, in humanities, the subsidy $\bar{\rho}_h h_0^*$ is 0.231 and h_0^* in the benchmark economy is 0.164. Thus, the subsidy is as high as 140.85% of the original research surplus. However, in the field of the aggregate, the subsidy is only about 3.12% ($= 0.372/11.936$). Thus, the amount of subsidy received by a professor in humanities is relatively large.

Table 4: Impacts of subsidy to professors' research

	τ=0.05%						τ=0.1%					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
Subsidy to professor												
$\bar{\rho}_h h_0^*$	0.372	0.517	0.410	0.362	0.231	0.487	0.741	1.033	0.819	0.723	0.440	0.970
$\bar{\rho}_h h_1^*$	0.493	0.793	0.553	0.387	0.285	0.681	0.983	1.585	1.106	0.773	0.542	1.359
Percentage change relative to the benchmark economy												
ε^*	4.22%	0.21%	0.66%	1.05%	39.41%	3.55%	7.53%	1.06%	1.31%	2.81%	100.04%	5.32%
$\mu^* - \varepsilon^*$	-2.83%	-0.31%	-0.63%	-0.89%	-23.44%	-2.13%	-5.45%	-0.77%	-1.26%	-1.90%	-53.45%	-3.84%
μ^*	0.13%	-0.09%	-0.09%	-0.07%	2.90%	0.25%	0.00%	0.00%	-0.18%	0.07%	10.89%	0.00%
q_0^*	-0.03%	-0.00%	-0.00%	-0.01%	-0.18%	-0.01%	-0.05%	-0.01%	-0.01%	-0.03%	-0.48%	-0.02%
q_1^*	-0.03%	-0.00%	-0.01%	-0.01%	-0.15%	-0.01%	-0.05%	-0.01%	-0.01%	-0.03%	-0.38%	-0.02%
m_0^*	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%	-6.30%	-0.96%	-1.45%	-1.98%	-56.59%	-4.56%
m_1^*	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%	-6.30%	-0.96%	-1.45%	-1.98%	-56.59%	-4.56%
p^*	-0.11%	0.08%	0.06%	0.06%	-1.70%	-0.05%	0.02%	-0.03%	0.11%	-0.10%	-7.39%	0.32%
s^*	0.10%	-0.02%	-0.01%	-0.04%	-1.28%	0.18%	-0.02%	0.12%	-0.01%	0.03%	-0.26%	-0.08%
$(1+\bar{\rho}_h)h_0^*$	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%	-0.05%	-0.16%	-0.13%	0.06%	211.64%	-0.60%
$(1+\bar{\rho}_h)h_1^*$	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%	-0.05%	-0.16%	-0.13%	0.06%	211.64%	-0.60%
x_0^*	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%	-0.90%	-0.01%	-0.05%	-0.16%	-51.73%	-0.14%
x_1^*	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%	-0.90%	-0.01%	-0.05%	-0.16%	-51.73%	-0.14%
w^*	0.00%	0.01%	0.01%	-0.00%	-0.47%	0.01%	0.00%	0.03%	0.01%	-0.00%	-1.35%	0.02%
k^*	0.03%	0.05%	0.07%	-0.04%	-20.43%	0.40%	0.01%	0.18%	0.15%	-0.07%	-48.13%	0.62%
π^*	-2.73%	-0.38%	-0.70%	-0.88%	-4.91%	-2.31%	-5.41%	-0.82%	-1.40%	-1.77%	-10.20%	-4.46%
y^*	0.00%	0.01%	0.01%	-0.00%	-0.48%	0.01%	0.00%	0.03%	0.01%	-0.00%	-1.36%	0.02%
Average lifetime utilities												
U	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%	-0.06%	-0.04%	-0.05%	-0.06%	-0.98%	-0.05%
U_I	-0.05%	-0.00%	-0.01%	-0.01%	0.02%	-0.07%	-0.06%	-0.04%	-0.02%	-0.06%	-0.91%	-0.02%
U_D	-0.03%	-0.02%	-0.02%	-0.03%	-0.37%	-0.04%	-0.07%	-0.04%	-0.05%	-0.06%	-1.04%	-0.06%
U_W	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%	-0.06%	-0.04%	-0.05%	-0.06%	-0.98%	-0.05%

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively.

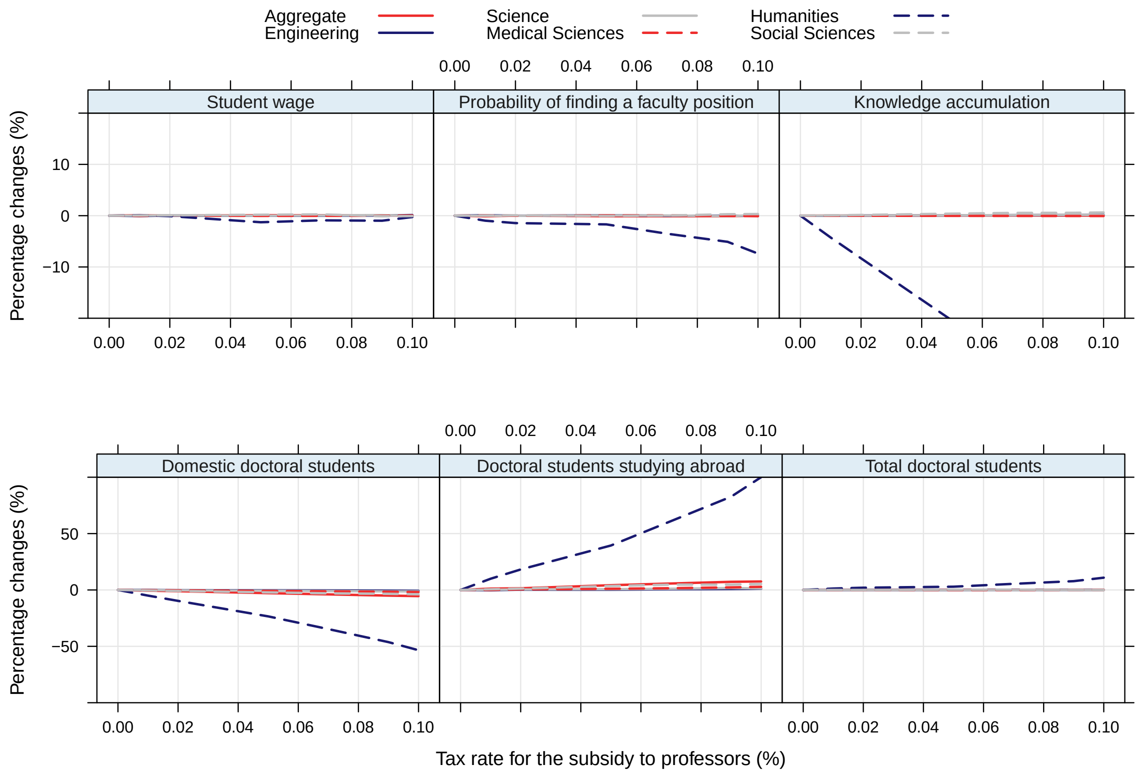

Figure 2: Subsidy to professors' research with various tax rates

Figure 2 further depicts the impacts of the subsidy on professors' research with various tax rates. We find that the effect of a subsidy to professors' research on knowledge accumulation k^* in most fields is positive but minor. For example, when $\tau = 0.1\%$, the largest effect of the subsidy to professors' research only increases k^* by 0.62% in social sciences. As the productivity differential is crucial in the mechanism, we move to provide counterfactual experiments to study the role of productivity differential in the next section.

5 Productivity Differentials

Our benchmark economy is calibrated to data from Taiwan, in which, on average, a productivity gap exists between professors who received doctoral training abroad and domestically. It is natural to ask: what would happen if our model is calibrated to a country much closer to the world research frontier? Do our policy implications discussed in Section 4 still hold when the productivity differential is negligible? This scenario can be applied to countries such as the United Kingdom, or the policy that allowing top foreign universities set up branch campuses in Taiwan.[36] Furthermore, how would the

[36]It is worth to note that this policy could narrow the research productivity gap between domestic and overseas-trained Ph.D. graduates. However, in addition to government subsidies, the policy still faces several challenges that are not considered here, such as the geographic, language, and institutional barriers.

policy effect change for countries with larger productivity differentials? To examine these questions, this section conducts counterfactual experiments with various productivity differentials to study the effects of the two subsidized policies. Specifically, we focus on the scenario with $\tau = 0.05\%$. All experiments are solved as steady states.[37]

We do the following process for a counterfactual experiment. First, given the parameter values in the benchmark economy, we assume there is no productivity differential, i.e., $B_0 = B_1$, to obtain a counterfactual benchmark economy. Others remain unchanged. Second, based on the counterfactual benchmark economy, a subsidy to domestic doctoral students or professors' research is implemented to conduct counterfactual policy experiments. Finally, we calculate the percentage changes of variables in the counterfactual policy experiment relative to those in the counterfactual benchmark economy to reflect the impact of the corresponding policy reform on the economy. The results are summarized in the columns of "$B_0 = B_1$" in Table 5 for the subsidy to domestic doctoral students and in Table 6 for the subsidy to professors' research. Moreover, the columns of "Baseline" in Table 5 and Table 6 repeat the results of policy experiments reported in Table 3 and Table 4, respectively.

We find that the counterfactual analysis with no productivity differentials enhances the policy implications in Section 4. On the one hand, as discussed in Section 4.1, a subsidy to domestic doctoral students attracts more students to enter domestic doctoral programs. The incentive to study domestically is even stronger if the productivity differential disappears. Therefore, many students who would have studied abroad choose to enter domestic doctoral programs now. As shown in Table 5, taking the aggregate as an example, ε^* decreases by 33.72% in the scenario with $B_0 = B_1$, while in the baseline it decreases by 21.68%. More domestic doctoral students increase the factor inputs in knowledge production. On the other hand, in the scenario without a productivity differential, the productivity between professors who graduated domestically and those who received training overseas is identical. There is no productivity loss when students choose domestic programs rather than overseas ones. Thus, the negative effect of the policy reform on knowledge production does not exist, and subsidizing domestic doctoral students promotes the accumulation of knowledge and increases output per labor. Therefore, in the baseline, in the fields where the productivity differential is actually relatively large (the aggregate, engineering, science, and social sciences), subsidizing domestic doctoral students results in lower knowledge accumulation, lower output per labor, and welfare loss. Closing the productivity gap (the scenario with $B_0 = B_1$) changes the impact and leads to higher knowledge accumulation, higher output per labor, and a welfare improvement. Besides, in the fields where the productivity differential is relatively small (medical sciences and humanities), the impact of the policy in the scenario with $B_0 = B_1$ is similar to that in the baseline, but enhanced. To conclude, we find a clear picture of the effect of subsidizing domestic doctoral students when $B_0 = B_1$: more domestic doctoral students as inputs in knowledge production yield higher knowledge accumulation, output, and welfare improvement.

With regard to the policy with a subsidy to professors' research, Table 6 suggests that closing the productivity gap enhances the incentives to study abroad. We take the aggregate as an example to

[37] We also conduct counterfactual experiments with various productivity differentials to study the impacts of a subsidy to a professor's wage. Due to the limited space, we do not report the results here. They are available upon request.

Table 5: Counterfactual analysis with subsidy to domestic doctoral students

	AGG		ENG		SCI		MED		HUM		SOC	
	Baseline	$B_0 = B_1$	Baseline	$B_0 = B_1$	Baseline	$B_0 = B_1$	Baseline	$B_0 = B_1$	Baseline	$B_0 = B_1$	Baseline	$B_0 = B_1$
Wage of domestic doctoral student												
s^*	2.469	2.336	2.326	2.169	2.453	2.308	2.898	2.860	1.802	1.799	1.034	1.026
$\bar{s}$	0.490	0.461	0.522	0.485	0.472	0.443	0.340	0.336	0.464	0.460	0.705	0.696
Percentage change relative to the benchmark economy												
ε^*	-21.68%	-33.72%	-22.13%	-46.30%	-19.44%	-30.87%	-13.86%	-15.61%	-6.06%	-6.22%	-90.48%	-98.79%
$\mu^* - \varepsilon^*$	16.57%	16.51%	21.19%	21.70%	18.13%	18.19%	10.64%	10.71%	3.44%	3.41%	64.45%	44.26%
μ^*	0.51%	-0.54%	3.03%	1.35%	2.38%	1.64%	0.37%	0.15%	-0.54%	-0.55%	-0.50%	7.92%
q_0^*	0.13%	0.17%	0.15%	0.27%	0.12%	0.18%	0.14%	0.16%	0.03%	0.03%	0.27%	0.11%
q_1^*	0.14%	0.16%	0.22%	0.30%	0.17%	0.21%	0.15%	0.16%	0.02%	0.02%	0.26%	0.16%
m_0^*	19.75%	16.51%	26.92%	21.70%	21.49%	18.19%	11.08%	10.71%	3.95%	3.41%	87.24%	44.26%
m_1^*	19.75%	16.51%	26.92%	21.70%	21.49%	18.19%	11.08%	10.71%	3.94%	3.41%	87.24%	44.26%
p^*	-0.56%	0.46%	-2.28%	-0.46%	-1.32%	-0.41%	-0.22%	0.00%	0.37%	0.37%	-4.67%	-10.43%
$s^* + \bar{s}$	0.24%	0.37%	0.22%	0.53%	0.28%	0.48%	0.27%	0.23%	0.03%	0.05%	0.35%	14.61%
h_0^*	-0.01%	-2.48%	3.64%	-0.21%	1.98%	-0.52%	-0.43%	-0.79%	-17.35%	-17.64%	11.03%	-1.85%
h_1^*	-0.01%	-2.48%	3.64%	-0.21%	1.98%	-0.52%	-0.43%	-0.79%	-17.35%	-17.64%	11.03%	-1.85%
x_0^*	2.55%	2.15%	0.36%	0.29%	0.65%	0.56%	0.83%	0.80%	3.44%	2.97%	1.84%	1.07%
x_1^*	2.55%	2.15%	0.36%	0.29%	0.65%	0.56%	0.83%	0.80%	3.44%	2.97%	1.84%	1.07%
w^*	-0.01%	0.06%	-0.67%	0.03%	-0.19%	0.04%	0.03%	0.05%	0.06%	0.06%	-0.38%	0.04%
k^*	-0.22%	2.10%	-4.21%	0.21%	-2.17%	0.50%	0.38%	0.75%	2.92%	2.96%	-10.64%	1.04%
π^*	-2.47%	-4.52%	3.28%	-0.50%	1.33%	-1.07%	-1.24%	-1.57%	-20.07%	-19.99%	9.04%	-2.88%
y^*	-0.01%	0.06%	-0.67%	0.03%	-0.19%	0.04%	0.03%	0.05%	0.06%	0.06%	-0.38%	0.04%
Average lifetime utilities												
U	-0.04%	0.01%	-0.40%	-0.01%	-0.14%	-0.01%	-0.02%	-0.00%	0.01%	0.01%	-0.26%	-0.01%
U_I	-0.05%	-0.02%	-0.40%	0.01%	-0.14%	-0.03%	-0.01%	0.01%	-0.02%	-0.01%	-0.26%	-2.85%
U_D	-0.03%	0.02%	-0.35%	0.05%	-0.10%	0.02%	0.01%	0.02%	-0.01%	-0.01%	-0.18%	0.04%
U_W	-0.03%	0.01%	-0.40%	-0.01%	-0.14%	-0.00%	-0.01%	0.00%	0.01%	0.01%	-0.26%	-0.01%

Note: "Baseline" is the result of subsidizing to domestic doctoral students reported in Table 3. "$B_0 = B_1$" represents the impact of subsidizing to domestic doctoral students in an economy without productivity differentials. Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively.

Table 6: Counterfactual analysis with subsidy to professors' research

	AGG		ENG		SCI		MED		HUM		SOC	
	Baseline	$B_0 = B_1$	Baseline	$B_0 = B_1$	Baseline	$B_0 = B_1$	Baseline	$B_0 = B_1$	Baseline	$B_0 = B_1$	Baseline	$B_0 = B_1$
Subsidy to professor												
$\bar{\rho}_h h_0^*$	0.372	0.427	0.517	0.662	0.410	0.482	0.362	0.374	0.231	0.260	0.487	0.568
$\bar{\rho}_h h_1^*$	0.493	0.427	0.793	0.662	0.553	0.482	0.387	0.374	0.285	0.260	0.681	0.568
Percentage change relative to the benchmark economy												
ε^*	4.22%	5.16%	0.21%	0.32%	0.66%	1.72%	1.05%	1.12%	39.41%	48.46%	3.55%	5.37%
$\mu^* - \varepsilon^*$	-2.83%	-2.65%	-0.31%	-0.27%	-0.63%	-0.73%	-0.89%	-0.87%	-23.44%	-24.77%	-2.13%	-1.83%
μ^*	0.13%	0.00%	-0.09%	-0.10%	-0.09%	0.10%	-0.07%	-0.07%	2.90%	5.29%	0.25%	0.00%
q_0^*	-0.03%	-0.02%	-0.00%	-0.00%	-0.00%	-0.01%	-0.01%	-0.01%	-0.18%	-0.23%	-0.01%	-0.01%
q_1^*	-0.03%	-0.02%	-0.00%	-0.00%	-0.01%	-0.01%	-0.01%	-0.01%	-0.15%	-0.18%	-0.01%	-0.01%
m_0^*	-3.31%	-2.65%	-0.36%	-0.27%	-0.73%	-0.73%	-0.92%	-0.87%	-25.78%	-24.77%	-2.59%	-1.83%
m_1^*	-3.31%	-2.65%	-0.36%	-0.27%	-0.73%	-0.73%	-0.92%	-0.87%	-25.78%	-24.77%	-2.59%	-1.83%
p^*	-0.11%	0.01%	0.08%	0.09%	0.06%	-0.15%	0.06%	0.06%	-1.70%	-3.76%	-0.05%	0.19%
s^*	0.10%	-0.09%	-0.02%	-0.06%	-0.01%	0.08%	-0.04%	-0.06%	-1.28%	-0.22%	0.18%	-0.14%
$(1+\bar{\rho}_h)h_0^*$	-0.06%	0.40%	-0.04%	0.00%	-0.07%	0.01%	0.04%	0.07%	114.23%	119.41%	-0.39%	0.05%
$(1+\bar{\rho}_h)h_1^*$	-0.06%	0.40%	-0.04%	0.00%	-0.07%	0.01%	0.04%	0.07%	114.23%	119.41%	-0.39%	0.05%
x_0^*	-0.47%	-0.37%	-0.01%	-0.00%	-0.02%	-0.02%	-0.07%	-0.07%	-22.92%	-22.00%	-0.08%	-0.05%
x_1^*	-0.47%	-0.37%	-0.01%	-0.00%	-0.02%	-0.02%	-0.07%	-0.07%	-22.92%	-22.00%	-0.08%	-0.05%
w^*	0.00%	-0.01%	0.01%	-0.00%	0.01%	-0.00%	-0.00%	-0.00%	-0.47%	-0.51%	0.01%	-0.00%
k^*	0.03%	-0.37%	0.05%	-0.00%	0.07%	-0.02%	-0.04%	-0.07%	-20.43%	-21.92%	0.40%	-0.05%
π^*	-2.73%	-2.35%	-0.38%	-0.33%	-0.70%	-0.62%	-0.88%	-0.86%	-4.91%	-3.73%	-2.31%	-1.89%
y^*	0.00%	-0.01%	0.01%	-0.00%	0.01%	-0.00%	-0.00%	-0.00%	-0.48%	-0.52%	0.01%	-0.00%
Average lifetime utilities												
U	-0.03%	-0.04%	-0.02%	-0.03%	-0.02%	-0.03%	-0.03%	-0.03%	-0.35%	-0.38%	-0.02%	-0.03%
U_I	-0.05%	-0.01%	-0.00%	-0.00%	-0.01%	-0.05%	-0.01%	-0.01%	0.02%	-0.39%	-0.07%	0.03%
U_D	-0.03%	-0.04%	-0.02%	-0.03%	-0.02%	-0.04%	-0.03%	-0.03%	-0.37%	-0.41%	-0.04%	-0.01%
U_W	-0.03%	-0.04%	-0.02%	-0.03%	-0.02%	-0.03%	-0.03%	-0.03%	-0.35%	-0.38%	-0.02%	-0.03%

Note: "Baseline" is the result of subsidizing on professors' research reported in Table 4. "$B_0 = B_1$" represents the impact of subsidizing on domestic doctoral students in an economy without productivity differentials. Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively.

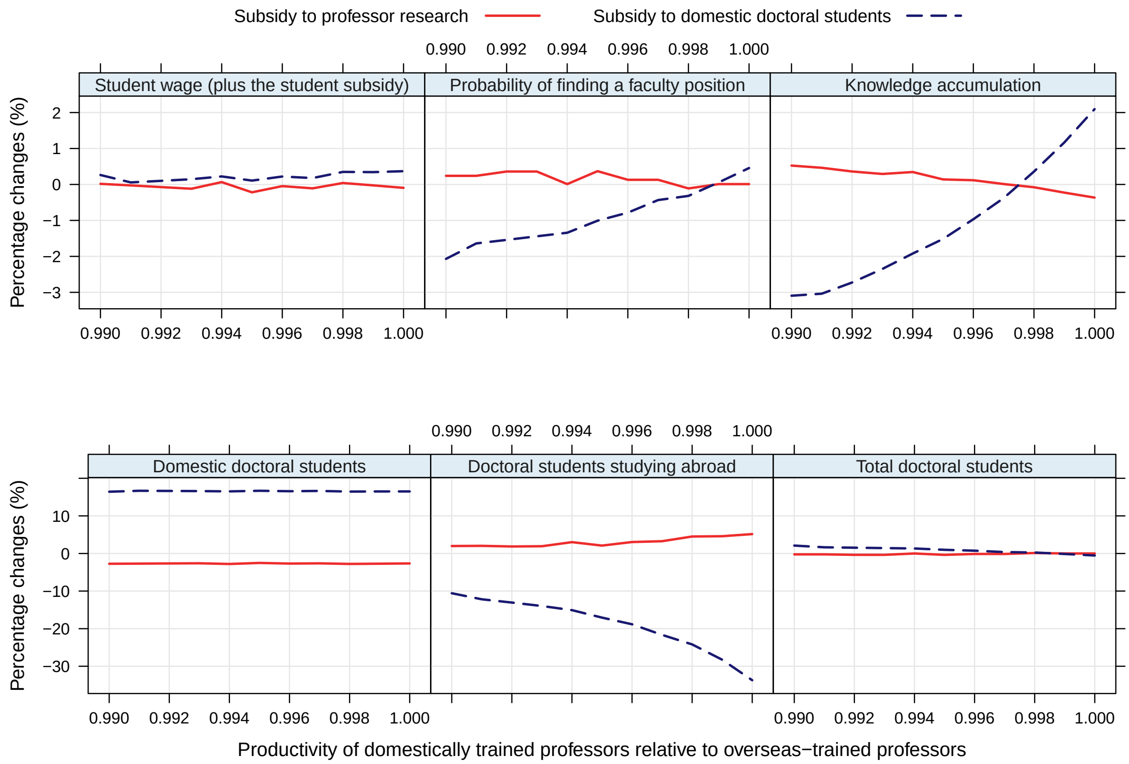

Figure 3: Effects of two subsidy reforms with various productivity differentials

provide the intuition. First of all, as discussed in Section 4.2, the policy with a subsidy to professors' research provides higher incentives to study abroad because of the productivity differential. In the scenario without a productivity gap, this effect disappears. However, the advantage of finding an academic position for international doctoral graduates still exists. Besides, the equilibrium student's wage becomes lower in the scenario without a productivity gap (for example, the change in s^* becomes -0.09% in the aggregate). Therefore, these two incentives push students to study abroad, and in the scenario without a productivity gap the change in ε^* becomes 5.16% from 4.22% in the baseline. Finally, fewer domestic doctoral students and no extra productivity gain from studying abroad result in less knowledge accumulation and lower output per labor. Therefore, when a significant productivity gap exists, a subsidy to professors' research slightly helps the accumulation of knowledge and increases output per labor. In contrast, if the productivity gap is minor and negligible, this policy has opposite effects on the economy.

Taking the field of aggregate as an example, Figure 3 depicts the impacts of the two subsidies with various productivity differentials, B_0/B_1. The scenarios are conducted at the tax rate $\tau = 0.05\%$. The x-axis represents B_0/B_1 ranging from 0.990 to 1. The y-axis is the percentage change of the variable under the subsidy relative to the benchmark economy.

Figure 3 suggests that the subsidy to domestic doctoral students attracts more labor inputs in knowledge production, i.e., more domestic doctoral students, and therefore knowledge accumulation

k^* increases in B_0/B_1. In contrast, the subsidy to professors' research has an opposite effect, and knowledge accumulation is decreasing in the productivity differential. The gain of this policy is mainly due to the increase in the number of professors who received overseas training. Thus, a larger productivity differential leads to higher knowledge accumulation. When the productivity gap is smaller, the gain from overseas training becomes minor, thereby reducing k^*. As a result, we find a single crossing of the two policies in the upper-right figure for knowledge accumulation when B_0/B_1 increases.

We conclude that, if a policy aims at increasing the number of domestic doctoral students, a subsidy to domestic doctoral students would work. But, the policy effect on knowledge accumulation is ambiguous, depending on the magnitude of its productivity differential. In contrast, subsidizing professors' research attracts more students to study abroad but fewer domestic doctoral students. The gain of subsidizing professor also depends on the productivity differential. Put differently, from the aggregate point of view (knowledge accumulation and the whole economy), a subsidy to domestic doctoral students is beneficial for countries with a smaller productivity differential in the academic sector, such as the UK. For countries with a relatively large productivity gap, a subsidy to professors' research is more desirable because the higher productivity of overseas training contributes to the home country.

6 Concluding Remarks

Taiwan is experiencing a decline in the number of doctoral students, and the faculty is aging in higher education. To examine various policies aiming at attracting more students to pursue doctoral degrees, we adopt a macroeconomic approach to quantify the impacts of these policies.

The Ph.D. labor market is crucial: it provides higher education and produces new knowledge. The accumulation of knowledge then contributes to labor productivity in the industry sector. To capture these features, we develop an occupational choice model in a five-period OLG framework in which professors overlap with doctoral students. Doctoral students are divided into two categories: international doctoral students (studying abroad) and domestic doctoral students (studying domestically). Professors hire domestic doctoral students to produce knowledge in the academic sector, where both professors and their doctoral students are the factor inputs. We also consider a productivity differential between professors who received doctoral training abroad versus domestically. All doctoral students face uncertainties in the process of becoming professors, and their outside option is to work in the industry sector. Thus, students make occupational choices according to their calibers, risks, and financial compensation.

We then calibrate the model to quantitatively evaluate a subsidy policy for domestic doctoral students or for professors' research. Our result suggests that the productivity differential between overseas-trained and domestically-trained professors plays an important role in the policy effect. When the productivity differential is minor, providing a subsidy to domestic doctoral students attracts more domestic students, promotes knowledge accumulation, and improves the average welfare. However, when the productivity differential is relatively large, the gains of having more professors with overseas training productivity become a dominant factor, and hence a subsidy policy for professors' research is more desirable when the policy aims at promoting knowledge accumulation in an economy.

The model we develop here is simple but tractable. It could be extended by considering other factors that may affect the Ph.D. labor market, such as the non-financial benefits of being a professor. For example, professors may enjoy the flexibility of choosing research topics and organizing time schedules; and a Ph.D. graduate with a strong publication record may affect his or her probability of finding an academic position. Moreover, our current model treats the market of higher education as homogeneous, whereas in Taiwan, a lower population growth in fact has a larger impact on private or teaching-oriented universities. Thus, considering the heterogeneity in higher education (research-oriented versus teaching-oriented universities or public versus private universities) in Taiwan may help to study the problem of faculty unemployment and its impact to research and the economy due to the exit or closure order of universities. The setting of heterogeneous universities may also be useful when studying issues related to the demand side of the higher education, such as college prestige and admission problems. Furthermore, relaxing the assumption so that research productivity directly depends on one's caliber could rich the framework and may bring more policy implications. Last but not least, our framework can be extended to discuss other higher education policies regarding the issue of Ph.D. talent gap in Taiwan, for instance subsidizing students to pursue doctoral degrees abroad, or subsidizing top foreign universities to set up branch campuses in Taiwan. As these topics are beyond the scope of our paper, they are left for future research.

Appendices

A The Phenomenons in Taiwan

This section summarizes two phenomenons in Taiwan. First, the trend of faculty aging is discussed. Regarding the issue of Ph.D. quotas in Taiwan, the second subsection provides specific evidences to support the argument that the Ph.D. quotas were not binding during the periods that we study.

A.1 The Trend of Aging Faculty Members in Taiwan

Figure A1 compares faculty members' age structure in Japan, Taiwan, and the UK. In 2012, the proportion of faculty members aged 50 and above was around 40 percent in the three countries. However, this proportion increased to over 60 percent in Taiwan of 2019, while it remained stable in Japan and declined to nearly 30 percent in the UK. The pattern implies that Taiwan's faculty members in higher education are aging, and more than 60 percent of Taiwan's current faculty members will retire in the next two decades.

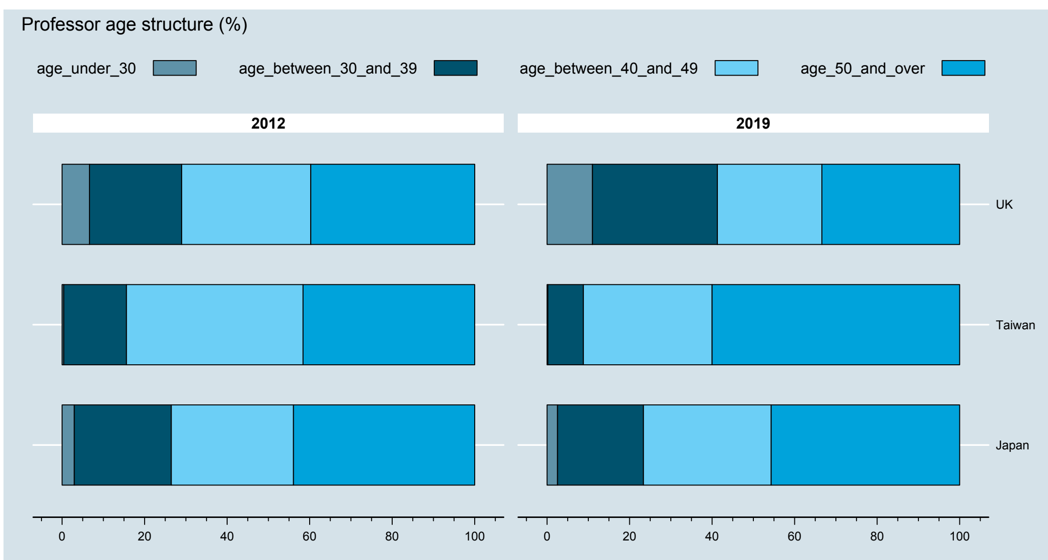

Figure A1: Faculty's age structure in Japan, Taiwan, and the UK

Data source: NPHRST (2022).

A.2 The Ph.D. Quotas in Taiwan

Every university in Taiwan faces the Ph.D. quotas set by MOE when Ph.D. admissions are issued. Hence, the issue of Ph.D. quotas is important as we are studying the higher education in Taiwan. Our model is calibrated at the national or at least field level, not to a specific department. Therefore, from the perspective of an aggregate level, the total number of domestic doctoral students would be flat (or even constant) over time if the quota is binding. In contrast, if the quota is not binding, the total number of domestic doctoral students would be endogenously determined by the demand and supply in the higher education market.

To see whether the Ph.D. quota is binding or not, we collect the total number of domestic doctoral students in Taiwan from MOE. As shown in the left panel of Figure A2, the number of domestic doctoral students (the red line) fluctuates over time, rapidly increasing since the year of 2000 and then starting to decline in 2010. This supports our argument that the Ph.D. quota in the aggregate level was not binding during the periods of time that our paper examines (2006-2015). Therefore, in our model, the number of domestic doctoral students is endogenously determined by students' occupational decisions and professors' demand.

Besides, in the left panel of Figure A2, we find that the number of domestic doctoral students is positively correlated with the number of assistant professors. The right panel of Figure A2 shows that the number of master's and undergraduate students has begun to fall around 2015. These two observations also support one important feature of our model settings: the foreseeable decline in demanding the higher education (a decrease in the number of undergraduate and master's students) affects current students' decisions to enter a Ph.D. program.

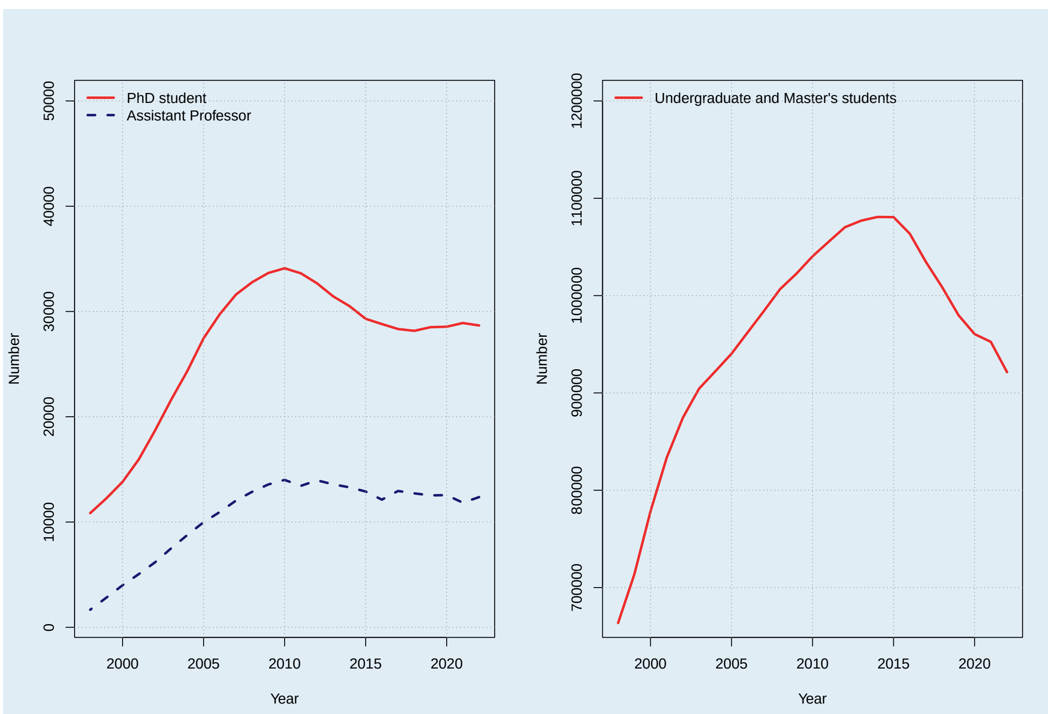

Figure A2: Number of domestic Ph.D. students and assistant professors in Taiwan

Data source: All series are obtained from MOE, Taiwan.

Moreover, we compare the Ph.D. quota with the enrollment rate at university level to indirectly examine whether the Ph.D. quotas is binding or not. If the quota is binding, the students who obtain admissions to domestic Ph.D. programs will be eager to enter the programs; thereby the enrollment rate would be nearly 100 percent. Figure A3 displays the Ph.D. quota (dash lines, using the right scale) and the enrollment rate of doctoral students (solid lines, using the left scale) for specific universities in Taiwan. Although the Ph.D. quotas and the enrollment rates are only available after 2017, which is beyond the periods that we examine, we still observe that the Ph.D. quotas were nearly fixed but the enrollment rates were much lower than 100 percent during 2017-2022. This evidence suggests that the Ph.D. quotas were not binding at university level.

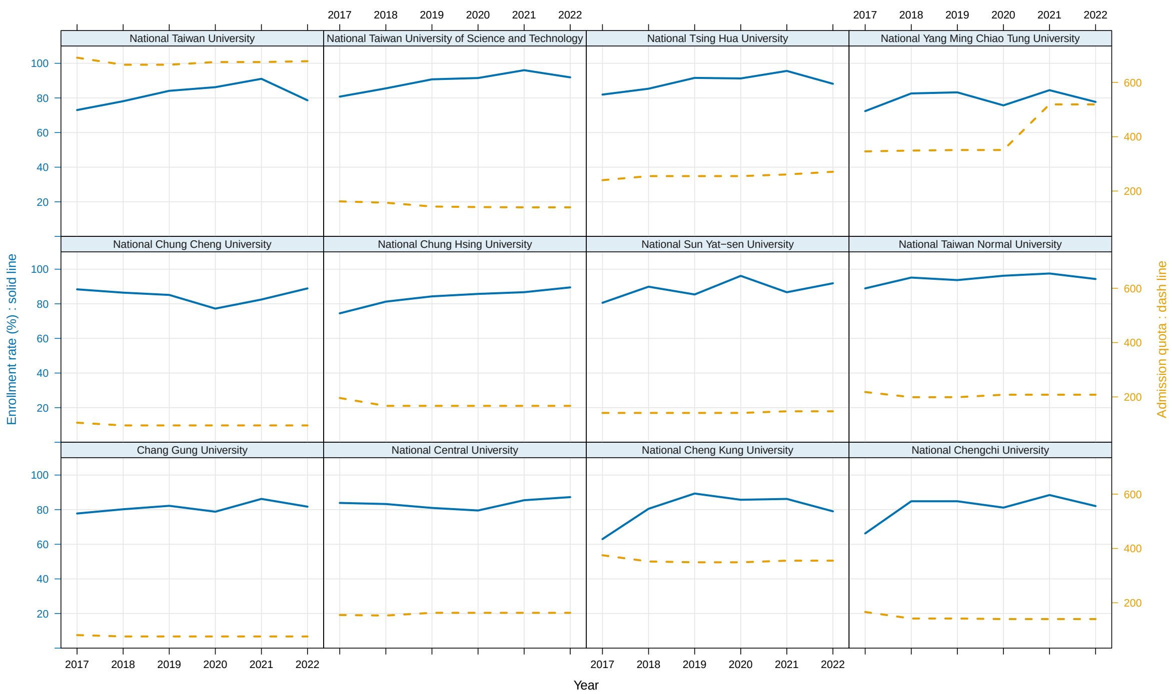

Figure A3: Ph.D. quotas and enrollment rates for specific universities in Taiwan

Data source: All series are obtained from the Ministry of Education (MOE), Taiwan..

B Equilibrium Knowledge-labor Ratio and Resource Constraint

Recall that the labor supply in efficiency units L_t is defined in (2). Moreover, in the steady state, $\mu_t = \mu^*$, $\varepsilon_t = \varepsilon^*$, $q_{\mathbb{I},t} = q^*_{\mathbb{I}}$, $p_{1,t} = p^*$, $p_{0,t} = \alpha p^*$, and $n_t = gn_{t-1}$. Hence, we can rewrite (2) as

$$\begin{aligned}
L_t =& n_{t-4}\Big(\sum_{j=0}^{4} g^t\Big)(1-\mu^*) + n_{t-4}\Big(\sum_{j=0}^{3} g^t\Big)\Big\{(\mu^*-\varepsilon^*)(1-q_0^*) + \varepsilon^*(1-\zeta)(1-q_1^*) \\
&+ \kappa\big[(\mu^*-\varepsilon^*)q_0^*(1-p^*) + \varepsilon^*(1-\zeta)q_1^*(1-\alpha p_1^*)\big]\Big\} \\
=& gL_{t-1},
\end{aligned}$$

Similarly, the accumulation of knowledge in the steady state is

$$K_t = n_{t-4}\Big(\sum_{j=0}^{3} g^t\Big)\big[(\mu^*-\varepsilon^*)q_0{}^* p^* x_0{}^* + \varepsilon^* q_1{}^*(1-\zeta)\alpha p^* x_1{}^*\big] + (1-\delta)K_{t-1} = gK_{t-1},$$

and then

$$K_{t-1} = \frac{n_{t-4}\left(\sum_{j=0}^{3} g^t\right)\left[(\mu^* - \varepsilon^*) q_0{}^* p^* x_0{}^* + \varepsilon^* q_1{}^* (1-\zeta)\alpha p^* x_1{}^*\right]}{g+\delta-1}.$$

Therefore, we have

$$\frac{K_{t-1}}{L_{t-1}} = \frac{g p^*}{g+\delta-1} \frac{(\mu^* - \varepsilon^*) q_0{}^* x_0{}^* + \varepsilon^* q_1{}^* (1-\zeta)\alpha x_1{}^*}{l^*} = k^*,$$

which is the equilibrium knowledge-labor ratio in (17) , where l^* is defined as

$$l^* = (1-\mu^*)(1+\hat{g}) + (\mu^* - \varepsilon^*)\left[1 - q_0{}^* + q_0{}^*(1-p^*)\kappa\right] + \varepsilon^*(1-\zeta)\left[1 - q_1{}^* + q_1{}^*(1-\alpha p^*)\kappa\right].$$

Moreover, recall the resource constraint in (5) and divide it by L_t to have

$$y_t - w_t = \frac{R_{0,t}(\pi_t x_{0,t} + d_t) + R_{1,t}(\pi_t x_{1,t} + d_t)}{L_t}.$$

In addition, in the steady state, we have

$$R_{0,t} = n_{t-4}\Big(\sum_{j=0}^{3} g^t\Big)(\mu^* - \varepsilon^*) q_0{}^* p^*,$$

and

$$R_{1,t} = n_{t-4}\Big(\sum_{j=0}^{3} g^t\Big)\varepsilon^* q_1{}^* (1-\zeta)\alpha p^*.$$

Therefore, the resource constraint in the steady state can be simplified to become equation (18), i.e.,

$$y^* - w^* = \frac{(\mu^* - \varepsilon^*) q_0{}^* p^* (\pi^* x_0{}^* + \bar{d}) + \varepsilon^* q_1{}^* (1-\zeta)\alpha p^* (\pi^* x_1{}^* + \bar{d})}{l^*}.$$

C Data Descriptions

Field classification: We follow the field classification defined by the Department of Statistics, Ministry of Education, Taiwan. The details can be found at http://english.moe.gov.tw.

Years required to complete a Ph.D. program: According to the 2014 Annual Employment Survey Report of Earned Doctorates (AESED), the average time to complete a Ph.D. program was 5.24 years, 5.69 years, and 6.22 years for 2001-2005, 2006-2010, and 2011-2015, respectively. Due to the increasing trend, the number of years required to complete a Ph.D. program in our calibration is set at 6. The survey was conducted by the Science and Technology Policy Research and Information Center, National Applied Research Laboratories.

Domestic doctoral graduation rate q_0^*: MOE reported the number of doctoral graduates and new doctoral students since 2005. As we observe from the data that it takes six years to complete a Ph.D. program, the domestic doctoral graduation rate is calculated as the sum of doctoral graduates in six years divided by the sum of fresh doctoral students six years ago. For example, the domestic doctoral graduation rate in 2015 is computed by the total number of doctoral graduates during 2010-2015 divided by the total number of fresh doctoral students during 2005-2010. We repeat the calculation to obtain the domestic doctoral graduation rate for each year and then take the average to be the data moment q_0^* for the calibration of b in every field.

Proportion of generation studying abroad ε^*: In the MOE data, we only have the total number of students who go abroad to study a doctoral program (aggregate). Divided by the number of college and master's graduates, we obtain the average proportion of the generation studying abroad in the field of aggregate, 0.017, during 2006-2015. However, field data are not available. To overcome the problem, we calculate the proportion of the generation studying abroad ε^* based on the proportion of the generation entering domestic doctoral programs. MOE reported the number of fresh domestic doctoral students and the number of domestic college and master's graduates each year. The number of fresh domestic doctoral students is divided by the number of domestic college and master's graduates to be the proportion of the generation entering domestic doctoral programs. Then we use the proportion of generation entering domestic doctoral programs in each field relative to the aggregate to adjust and compute the proportion of the generation studying abroad in each field. For example, the proportion of the generation entering domestic doctoral programs is 0.023 and 0.033 for the aggregate and engineering, respectively. Given that ε^* in the aggregate is 0.017, the proportion of the generation studying abroad in engineering is calculated by $\frac{0.033}{0.023} \times 0.017 = 0.024$.

Gross growth rate of generation g: The generation n_t in our model is defined as the total number of undergraduates and master's students. The numbers of undergraduates and master's students are both available in MOE data. To compute g in each field, we first calculate the annualized geometric mean of the gross growth rate for the total number of undergraduates and master's students from 2006 to 2015. Second, the average gross growth rate of the population is adjusted by the length of the model period (8 years) to obtain g. For example, the annualized geometric mean is 0.989 in engineering and hence we have $g = 0.919$ for engineering ($0.989^8 = 0.919$) in the calibration.

Student-professor ratio a: The MOE data provided the numbers of students and professors at all ranks. According to the definition of the student-professor ratio, the ratio is the stock of students divided by the stock of professors each year. The stock of students includes undergraduates and master's students who enroll in public or private universities. The stock of professors includes professors, associate professors, and assistant professors (both public and private universities). We calculate the student-professor ratio in each year during 2006-2015. Then we use the average value as a.

Wage of professors $\bar{d}$: The salary for professors of the same rank is fairly homogeneous in Taiwan, regardless of field. Seniority results in a slight difference. The average annual salary of an assistant professor in a public university in Taiwan is about 1.05 million; it is 1.18 million for an associate professor, and 1.36 million for a full professor. Here we also consider the yearly bonus (which equals 1.5 monthly wages) that Taiwanese civil servants usually obtain to represent the bonus for professors. To compute $\bar{d}$, we assume a young agent after graduation works at the rank of assistant professor for one-third of the model periods, at the rank of associate professor for one-third of the model periods, and the rest at the rank of full professor. Then, adjusted by the length of the model period, we obtain a weighted average wage for professors of 9.585 million (TWD). The data are from the salary table for National Chung Hsing University, which is the same as for all universities in Taiwan.

Wage of doctoral student s^*: Data for doctoral students' wages are very limited. Thus, we adopt small-sample survey data. The National Taiwan University (NTU) Graduate Student Association conducted a survey on graduate students' income and expenditure in 2010. The survey reported the monthly wage of a doctoral student in every field of NTU. Following the field classification of MOE, we compute the weighted average of the monthly wage for each field (weighted by the number of doctoral students in each field). The aggregate wage is a weighted average of the five fields we discuss in this paper. Then, a 12-months of income is computed as the yearly income of a doctoral student. Furthermore, the targeted wages of a doctoral student (s^*) in the fields of aggregate, engineering, science, and medical sciences contain six-years of income as a doctoral student plus two more years' worth as a postdoc. According to the Ministry of Science and Technology in Taiwan, the standard monthly income is 56,650 TWD for a first-year postdoc and 58,710 TWD for a second-year postdoc. These are translated to a yearly basis and are included in the targeted wage of the above four fields. In contrast, it usually takes longer to complete a doctoral program in the fields of humanities and social sciences, but postdoctoral experience is not required when searching for an academic position. To reflect this fact, we exclude the periods for postdocs and only calculate eight years of a doctoral student's income as the targeted wage (s^*) for the two fields.

Knowledge output x_0^* and x_1^*: To measure the knowledge output of professors with a domestic degree x_0^* and that of professors with an international degree x_1^* in each field, we use research grants as a proxy. The following steps are applied. First, we calculate the average research grants per professor in each field (without distinguishing domestic from international doctoral degrees) using the data in the Government Research Bulletin (GRB). The details of the GRB can be found at https://www.grb.gov.tw/index. There are two sets of statistics in GRB. The base GRB provides the statistics of research grants supported by the government budget in each field during 2003-2012, mainly grants from MOST. In addition, GRB separately provides the statistics of grants supported by other government institutions (the MOE, Presidential Palace, Academia Sinica, and National History Museum). We include both statistics to obtain the average research grants per professor in each field (without distinguishing domestic from international doctoral degrees). Second, the MOST website provides the information of each research grant, including the name of the principal investigator (PI), the field, and the amount of the grant. On the MOST website, some PIs also provide school names and the year they obtained their doctoral degrees. With these two datasets on the MOST website, we are able to compute the ratio of PIs with a domestic degree to those with an international degree. The ratio is 1.0652, 1.3418, 0.7401, 1.4380, 0.7468, and 0.8829 for the aggregate and the fields of engineering, science, medical sciences, humanities, and social sciences, respectively. Similarly, we compute the ratio of research grants obtained by PIs with a domestic degree to those with an international degree (per PI per year and inflation-adjusted). The ratio of research grants is 0.7542, 0.6518, 0.7410, 0.9354, 0.8116, and 0.7141 for aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. Third, with the average research grants per professor obtained in the first step and the ratios of PIs and research grants obtained in the second step, we are now ready to compute the average research grant obtained by professors with a domestic degree x_0^* and that for professors with an international degree x_1^*. The results of x_0^* and x_1^* are reported in Table 2. They are our targets to calibrate B_0 and B_1. It is worth to note that in our calculation, we exclude the PIs with two doctoral degrees and only consider those who obtained their doctoral degree within 16 years. The results are similar when we consider the PIs who graduated within 20 years.

Wage premium of Ph.D. Worker κ: In 2017, the MOL in Taiwan released a report entitled "The Wage and Employment Guidance for College Graduates (WEGG)". The report contains statistics of the wage and employment status of graduates during the period from 2011 to 2016. In WEGG, we have the number of workers by field (denoted by i) and by industry (denoted by j); therefore, we are able to compute the working-industry distribution of graduates from different fields (denoted by l_{ij}). In addition, WEGG provides the average wage by education level (denoted by e) and by industry (denoted by j). We denote these wages as ω_{ej}. Then, the average wage of graduates with the education level e in the field i is computed by $\omega_{ie} = \sum_j l_{ij}\omega_{ej}$. Furthermore, according to the MOE statistics, we have the number of doctoral graduates each year. We then compute the employment rate of doctoral graduates and use it to adjust the average wage of Ph.D. graduates. Finally, a wage premium κ in a field is obtained by computing the ratio of the adjusted average wage of Ph.D. graduates to that of college graduates. It is worth to note that the field classification in WEGG is slightly different from that of MOE. Therefore, the wage premium κ for the field of science is the weighted average on life science, natural science, mathematics, and statistics. The details can be found at https://yoursalary.taiwanjobs.gov.tw.

Proportion of generation entering doctoral programs μ^*: By definition, the proportion of the generation who decide to enter doctoral programs consists of two parts: the proportion of the generation who decide to pursue international doctoral degrees (ε^*) and the proportion of the generation who decide to enter domestic doctoral programs. As we discussed, they are calculated with the MOE data. Therefore, μ^* is the sum of these two proportions.

Wage in industry w^*: The WEGG reported average monthly wages by fields for full-time jobs. Considering the possibility of unemployment and part-time positions, we adjust the average monthly wage for a full-time job using the percentage of having a full-time job to obtain the expected monthly wage. Then, the expected yearly wage is calculated with an additional yearly bonus (which equals 1.5 months of wage in all fields). Finally, the expected yearly wage is adjusted according to the length of the model period to obtain the target value. It is worth to note that the field classification of WEGG is slightly different from that of the MOE. Thus, the target value of the average wage for science is the weighted average of life science, natural science, mathematics, and statistics. The details can be found at https://yoursalary.taiwanjobs.gov.tw.

D Equilibrium Subsidy Levels for a Flat Tax Rate

D.1 Subsidy to Domestic Doctoral Students

First, we consider a subsidy to student wage financed by a flat income tax, τ. The total subsidy amount received by domestic doctoral students is

$$\bar{s}(m_{0,t}R_{0,t} + m_{1,t}R_{1,t}),$$

which is financed by the total tax revenue

$$\tau\big[(\pi_t h_{0,t} + d_t)R_{0,t} + (\pi_t h_{1,t} + d_t)R_{1,t} + w_t L_t + (s_t + \bar{s})(m_{0,t}R_{0,t} + m_{1,t}R_{1,t})\big].$$

In addition, the resource constraint in equation (5) becomes

$$\begin{aligned} Y_t &= (1-\tau)\big[(\pi_t h_{0,t} + d_t)R_{0,t} + (\pi_t h_{1,t} + d_t)R_{1,t} + w_t L_t + (s_t + \bar{s})(m_{0,t}R_{0,t} + m_{1,t}R_{1,t})\big] + \bar{s}(m_{0,t}R_{0,t} + m_{1,t}R_{1,t}) \\ &= (\pi_t h_{0,t} + d_t)R_{0,t} + (\pi_t h_{1,t} + d_t)R_{1,t} + w_t L_t + (s_t + \bar{s})(m_{0,t}R_{0,t} + m_{1,t}R_{1,t}). \end{aligned}$$

That is, $Y_t = (1-\tau)Y_t + \bar{s}(m_{0,t}R_{0,t} + m_{1,t}R_{1,t})$. Hence, the total amount of subsidy is a fraction of total output, and we have

$$\bar{s} = \frac{\tau Y_t}{(m_{0,t}R_{0,t} + m_{1,t}R_{1,t})}.$$

In the steady state, the common factor $n_{t-4}\left(\sum_{j=0}^{3} g^t\right)$ is cancelled out at the right-hand side above, and hence $\bar{s}$ is pinned down by

$$\bar{s} = \frac{\tau y^* l^*}{m_0{}^*(\mu^* - \varepsilon^*)q_0{}^* p^* + m_1{}^* \varepsilon^* q_1{}^*(1-\zeta)\alpha p^*}.$$

Moreover, the expected utility of becoming a worker in the steady state is pinned down by

$$\sum_{j=0}^{4} \beta^j \ln(w^*) + \sum_{j=0}^{4} \beta^j \ln(1-\tau),$$

while the expected utility of becoming a domestic doctoral student for agent i is given by

$$\begin{aligned} \ln(s^* + \bar{s}) \; &+ f_t(i)\left[p^* \sum_{j=1}^{4} \beta^j \ln(\bar{d} + h_0^*) + (1-p^*) \sum_{j=1}^{4} \beta^j \ln(\kappa w^*)\right] \\ &+ \big(1 - f_t(i)\big)\left(\sum_{j=1}^{4} \beta^j \ln(w^*)\right) + \sum_{j=0}^{4} \beta^j \ln(1-\tau). \end{aligned}$$

On the other hand, since international doctoral students do not pay the proposed tax in their first period, the expected lifetime utility for an international doctoral student i becomes

$$\ln(\psi f_t(i)) + v_1 + f_t(i)\left(\alpha p^* \sum_{j=1}^{4} \beta^j \ln(\bar{d} + h_1^*) + (1-\alpha p^*) \sum_{j=1}^{4} \beta^j \ln(\kappa w^*)\right)$$
$$+ \big(1 - f_t(i)\big)\left(\sum_{j=1}^{4} \beta^j \ln(w^*)\right) + \sum_{j=1}^{4} \beta^j \ln(1-\tau).$$

Therefore, the occupational-choice constraint of becoming an international doctoral student becomes

$$\ln\big(\frac{\psi b}{s^* + \bar{s}}\big) + v_1 - \ln(1-\tau) = b\varepsilon^* - \hat{\beta} b e^{-b\varepsilon^*}\left[\alpha p^* \ln(\bar{d} + h_1{}^*) - p^* \ln(\bar{d} + h_0{}^*) - p^*(\alpha - 1)\ln(\kappa w^*)\right]$$

and the occupational-choice constraint of becoming a doctoral student becomes

$$\ln\left(\frac{s^* + \bar{s}}{w^*}\right) = -\hat{\beta} b e^{-b\mu^*}\left[p^* \ln(\bar{d} + h_0{}^*) + \big(1 - p^*\big)\ln(\kappa w^*) - \ln w^*\right].$$

Then, the average utility levels of international doctoral students, domestic doctoral students, and workers can be derived accordingly.

D.2 Subsidy to Professors' Research

Second, we consider a subsidy to professors proportional to their research surplus. Under this policy, a professor receives a subsidy of $\bar{\rho}_h h_{0,t}$ or $\bar{\rho}_h h_{1,t}$ in period t. Similar to the previous policy reform, this subsidy is financed by a flat income tax. The total subsidy amount received by professors is

$$\bar{\rho}_h\ (h_{0,t} R_{0,t} + h_{1,t} R_{1,t}),$$

whereas the total tax revenue in each period t is

$$\tau\big\{[(\pi_t h_{0,t} + \bar{\rho}_h) + d_t] R_{0,t} + [(\pi_t h_{1,t} + \bar{\rho}_h) + d_t] R_{1,t} + w_t L_t + s_t\ (m_{0,t} R_{0,t} + m_{1,t} R_{1,t})\big\}.$$

Similar to the analysis in the policy reform of student subsidy, we rewrite the resource constraint and the total amount of the subsidy is a fraction of total output. That is,

$$\bar{\rho}_h\ (h_{0,t} R_{0,t} + h_{1,t} R_{1,t}) = \tau Y_t.$$

Likewise, in the steady state, $\bar{\rho}_h$ is pinned down by

$$\bar{\rho}_h = \frac{\tau y^* l^*}{h_0{}^*(\mu^* - \varepsilon^*) q_0{}^* p^* + h_1{}^* \varepsilon^* q_1{}^*(1-\zeta)\alpha p^*}.$$

Under such subsidy, the expected utility of becoming a domestic doctoral student for agent i is given by

$$\ln s^* + f_t(i)\left(p^* \sum_{j=1}^{4} \beta^j \ln(\bar{d} + (1+\bar{\rho}_h) h_0^*) + (1-p^*) \sum_{j=1}^{4} \beta^j \ln(\kappa w^*)\right)$$
$$+ \big(1 - f_t(i)\big)\left(\sum_{j=1}^{4} \beta^j \ln(w^*)\right) + \sum_{j=0}^{4} \beta^j \ln(1-\tau),$$

while the expected lifetime utility for an international doctoral student i becomes

$$\ln(\psi f_t(i)) + v_1 + f_t(i)\left(\alpha p^* \sum_{j=1}^{4} \beta^j \ln(\bar{d} + (1+\bar{\rho}_h)h_1^*) + (1-\alpha p^*) \sum_{j=1}^{4} \beta^j \ln(\kappa w^*)\right)$$
$$+ \big(1 - f_t(i)\big)\left(\sum_{j=1}^{4} \beta^j \ln(w^*)\right) + \sum_{j=1}^{4} \beta^j \ln(1-\tau),$$

and the worker's expected utility in the steady state is unchanged and is given by $\sum_{j=0}^{4} \beta^j \ln(w^*) + \sum_{j=0}^{4} \beta^j \ln(1-\tau)$. Therefore, the occupational-choice constraint of becoming an international doctoral student becomes

$$\begin{aligned} &\ln\big(\frac{\psi b}{s^*}\big) + v_1 - \ln(1-\tau) \\ &= b\varepsilon^* - \hat{\beta} b e^{-b\varepsilon^*}\big\{\alpha p^* \ln[\bar{d} + (1+\bar{\rho}_h)h_1{}^*] - p^* \ln[\bar{d} + (1+\tau_h)h_0{}^*] - p^*(\alpha-1)\ln(\kappa w^*)\big\} \end{aligned}$$

and the occupational-choice constraint of becoming a doctoral student becomes

$$\ln\left(\frac{s^*}{w^*}\right) = -\hat{\beta} b e^{-b\mu^*}\big\{p^* \ln[\bar{d} + (1+\bar{\rho}_h)h_0{}^*] + \big(1-p^*\big)\ln(\kappa w^*) - \ln w^*\big\}.$$

Using the above expressions, we can derive the average utility levels of domestic doctoral students, international doctoral students, and workers, accordingly.

D.3 Subsidy to Professor's Wage

Lastly, we consider a subsidy to professors proportional to their wages. Under this policy, a professor receives a subsidy of $\widetilde{d}_t$ in period t, which is financed by a flat income tax. That is,

$$\widetilde{d}_t\ (R_{0,t} + R_{1,t}) = \tau Y_t.$$

In the steady state, $\widetilde{d}_t = \widetilde{d}$ and is pinned down by

$$\widetilde{d} = \frac{\tau y^* l^*}{(\mu^* - \varepsilon^*)q_0{}^* p^* + \varepsilon^* q_1{}^*(1-\zeta)\alpha p^*}$$

Under such subsidy, the expected utility of becoming a domestic doctoral student for agent i is given by

$$\ln s^* \ + f_t(i)\left(p^* \sum_{j=1}^{4} \beta^j \ln(\bar{d} + \widetilde{d} + h_0^*) + (1-p^*) \sum_{j=1}^{4} \beta^j \ln(\kappa w^*)\right)$$
$$+ \big(1 - f_t(i)\big)\left(\sum_{j=1}^{4} \beta^j \ln(w^*)\right) + \sum_{j=0}^{4} \beta^j \ln(1-\tau),$$

while the expected lifetime utility for an international doctoral student i becomes

$$\ln(\psi f_t(i)) + v_1 \ + f_t(i)\left(\alpha p^* \sum_{j=1}^{4} \beta^j \ln(\bar{d} + \widetilde{d} + h_1^*) + (1-\alpha p^*) \sum_{j=1}^{4} \beta^j \ln(\kappa w^*)\right)$$
$$+ \big(1 - f_t(i)\big)\left(\sum_{j=1}^{4} \beta^j \ln(w^*)\right) + \sum_{j=1}^{4} \beta^j \ln(1-\tau),$$

and the worker's expected utility in the steady state is still given by $\sum_{j=0}^{4}\beta^{j}\ln(w^{*})+\sum_{j=0}^{4}\beta^{j}\ln(1-\tau)$. Therefore, the occupational-choice constraint of becoming an international doctoral student becomes

$$\ln\Big(\frac{\psi b}{s^{*}}\Big)+v_{1}-\ln(1-\tau)=b\varepsilon^{*}-\hat{\beta}be^{-b\varepsilon^{*}}\big[\alpha p^{*}\ln(\bar{d}+\widetilde{d}+h_{1}{}^{*})-p^{*}\ln(\bar{d}+\widetilde{d}+h_{0}{}^{*})-p^{*}(\alpha-1)\ln(\kappa w^{*})\big]$$

and the occupational-choice constraint of becoming a doctoral student becomes

$$\ln\left(\frac{s^{*}}{w^{*}}\right)=-\hat{\beta}be^{-b\mu^{*}}\big[p^{*}\ln(\bar{d}+\widetilde{d}+h_{0}{}^{*})+\big(1-p^{*}\big)\ln(\kappa w^{*})-\ln w^{*}\big].$$

Using the above expressions, we can derive the average utility levels of domestic doctoral students, international doctoral students, and workers as follows.

$$\begin{aligned}U_{D}\ &=\ln s^{*}+\frac{e^{-b\varepsilon^{*}}-e^{-b\mu^{*}}}{\mu^{*}-\varepsilon^{*}}\left[p^{*}u_{0}^{d}+\big(1-p^{*}\big)u_{K}-u_{W}\right]+u_{W}\\&\quad+(1+\hat{\beta})\ln(1-\tau)\end{aligned}$$

for domestic doctoral students,

$$\begin{aligned}U_{I}\ &=\ln\psi+v_{1}+\ln b-\frac{b\varepsilon^{*}}{2}+\frac{1-e^{-b\varepsilon^{*}}}{\varepsilon^{*}}\left[\alpha p^{*}u_{1}^{d}+\big(1-\alpha p^{*}\big)u_{K}-u_{W}\right]+u_{W}\\&\quad+\hat{\beta}\ln(1-\tau)\end{aligned}$$

for international doctoral students, and

$$U_{W}=\ln w^{*}+u_{W}+(1+\hat{\beta})\ln(1-\tau)$$

for workers, where $u_{0}^{d}=\hat{\beta}\ln(\bar{d}+\widetilde{d}+h_{0}{}^{*})$, $u_{1}^{d}=\hat{\beta}\ln(\bar{d}+\widetilde{d}+h_{1}{}^{*})$, $u_{K}=\hat{\beta}\ln\kappa w^{*}$, and $u_{W}=\hat{\beta}\ln w^{*}$. The average welfare is

$$U\equiv\varepsilon^{*}U_{I}+(\mu^{*}-\varepsilon^{*})U_{D}+(1-\mu^{*})U_{W}.$$

We present the results of the subsidy in Table A1. Notably, subsidizing professor's wage has a similar impact to subsidizing their research. This policy reform encourages studying overseas in all fields, as international doctoral graduates have higher chances of finding a faculty position, just like the case with subsidizing professors' research. Similarly, the number of domestic doctoral students per professor (m_0^* and m_1^*) decreases, as do knowledge outputs per professor (x_0^* and x_1^*). The accumulation of knowledge (k^*) increases in the fields of engineering, science, and social sciences due to productivity differentials and decreases in medical sciences and humanities because the productivity gaps in these fields are relatively small. However, unlike the subsidy to professors' research, which raises the number of total doctoral students in the aggregate, the subsidy to professor's wage reduces the number of total doctoral students in the aggregate (i.e., μ^* decreases). Consequently, the accumulation of knowledge (k^*) decreases. In terms of welfare, we find that this policy reform results in welfare losses in all fields. This result is similar to the case of subsidizing professors' research, except for the field of humanities. In the field of humanities, subsidizing professor's wage leads to more individuals opting to become doctoral students than in the scenario with a subsidy to professors' research. Therefore, the probability of finding a faculty position (p^*) decreases more, leading to higher welfare losses.

Table A1: Impacts of subsidy to professor's wage

	τ=0.05%						τ=0.1%					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
Wage of professors' wage												
$\overline{d}$	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585
$\widetilde{d}$	0.425	0.639	0.475	0.373	0.260	0.564	0.851	1.278	0.950	0.745	0.516	1.129
Percentage change relative to the benchmark economy												
ε^*	3.31%	0.43%	0.66%	1.05%	46.34%	2.37%	6.93%	0.64%	1.53%	2.81%	98.31%	4.73%
$\mu^* - \varepsilon^*$	-2.62%	-0.31%	-0.63%	-0.89%	-24.69%	-1.71%	-5.23%	-0.61%	-1.26%	-1.90%	-52.82%	-3.41%
μ^*	-0.13%	0.00%	-0.09%	-0.07%	5.08%	0.00%	-0.13%	-0.09%	-0.09%	0.07%	10.53%	0.00%
q_0^*	-0.02%	0.00%	0.00%	-0.01%	-0.22%	-0.01%	-0.04%	0.00%	-0.01%	-0.03%	-0.47%	-0.01%
q_1^*	-0.02%	0.00%	-0.01%	-0.01%	-0.18%	-0.01%	-0.04%	-0.01%	-0.01%	-0.03%	-0.37%	-0.01%
m_0^*	-3.02%	-0.38%	-0.73%	-0.92%	-27.23%	-2.04%	-6.03%	-0.75%	-1.47%	-1.98%	-55.97%	-4.06%
m_1^*	-3.02%	-0.38%	-0.73%	-0.92%	-27.23%	-2.04%	-6.03%	-0.75%	-1.47%	-1.98%	-55.97%	-4.06%
p^*	0.13%	-0.01%	0.06%	0.06%	-3.60%	0.14%	0.14%	0.07%	0.02%	-0.10%	-7.12%	0.28%
s^*	-0.12%	-0.02%	-0.01%	-0.04%	-0.33%	-0.25%	-0.25%	-0.04%	-0.01%	0.03%	-0.96%	-0.52%
h_0^*	-3.10%	-0.40%	-0.73%	-0.95%	-27.24%	-2.26%	-6.20%	-0.78%	-1.47%	-1.92%	-56.03%	-4.51%
h_1^*	-3.10%	-0.40%	-0.73%	-0.95%	-27.24%	-2.26%	-6.20%	-0.78%	-1.47%	-1.92%	-56.03%	-4.51%
x_0^*	-0.43%	-0.01%	-0.02%	-0.07%	-24.24%	-0.06%	-0.86%	-0.01%	-0.05%	-0.16%	-51.13%	-0.12%
x_1^*	-0.43%	-0.01%	-0.02%	-0.07%	-24.24%	-0.06%	-0.86%	-0.01%	-0.05%	-0.16%	-51.13%	-0.12%
w^*	0.00%	0.01%	0.01%	0.00%	-0.50%	0.01%	0.00%	0.02%	0.01%	0.00%	-1.33%	0.02%
k^*	-0.01%	0.07%	0.07%	-0.04%	-21.51%	0.28%	-0.01%	0.12%	0.16%	-0.07%	-47.53%	0.56%
π^*	-2.69%	-0.40%	-0.70%	-0.88%	-4.23%	-2.21%	-5.40%	-0.77%	-1.42%	-1.77%	-10.67%	-4.40%
y^*	0.00%	0.01%	0.01%	0.00%	-0.51%	0.01%	0.00%	0.02%	0.01%	0.00%	-1.34%	0.02%
Average lifetime utilities												
U	-0.03%	-0.02%	-0.02%	-0.03%	-0.37%	-0.03%	-0.06%	-0.04%	-0.05%	-0.06%	-0.96%	-0.05%
U_I	-0.03%	-0.02%	-0.02%	-0.01%	-0.38%	-0.04%	-0.08%	-0.03%	-0.06%	-0.06%	-0.90%	-0.08%
U_D	-0.02%	-0.03%	-0.02%	-0.03%	-0.41%	-0.05%	-0.06%	-0.05%	-0.05%	-0.06%	-1.02%	-0.09%
U_W	-0.03%	-0.02%	-0.02%	-0.03%	-0.37%	-0.02%	-0.06%	-0.05%	-0.05%	-0.06%	-0.97%	-0.05%

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively.

E Robustness Tests

This section provides robustness tests for the gross growth rate of generation (g), the depreciation rate of knowledge (δ), the parameter that governs the elasticity of substitution between professor and Ph.D. student (θ_x), the parameter that governs the elasticity of substitution between knowledge and labor (θ_Y), and the ratio of brain drain (ζ). To avoid confusion, the calibrated economy reported in the main text (Tables 1 and 2) is renamed as "the baseline".

In every test, we modify the parameter that we are interested in from its baseline value to a new setting, while leaving the other common parameters listed in Table 1 unchanged. We re-calibrate each test to obtain the corresponding benchmark economy. Then, based on the corresponding benchmark economy, we study the two policy experiments: (1) a subsidy to domestic doctoral students; and (2) a subsidy to professor's research. All policy experiments are conducted in the scenario of $\tau = 0.05\%$. Finally, percentage changes relative to the corresponding benchmark economy are calculated and compared with the results of the baseline which were reported in Tables 3 and 4. The results of robustness tests are summarized in Table A2-A16. The details are discussed as follows.

E.1 Tests for the Gross Growth Rate of Generation

In the baseline, the gross growth rate of generation in each field is calculated based on the data of 2006-2015. As shown in the left panel of Table A2, the gross growth rates of generation in all fields, excluding medical sciences and humanities, are below one, indicating a decline in these generations. Indeed, the decrease in generations is influenced by reduced fertility rates in Taiwan. Specifically, Taiwan experienced significantly lowest-low birth rates in the past two decades and these generations became undergraduates after 2015. This implies that the gross growth rate of generation after the data period that we study would be even lower. To examine the effect of a lower generation growth rate on our policy experiments, we re-calculate g by the MOE data from 2006 to 2022 for every field, while other data moments and targets remain unchanged. Using the new values of g, the model is re-calibrated to fit those unchanged data targets. The new calibrated result is reported in the right panel of Table A2. Based on the new calibrated result, the two policy experiments are conducted again and summarized in Tables A3 and A4.

First of all, we observe that the new values of g are all lower than the baseline values, except for science. This is consistent with the experience of decreasing fertility rates in Taiwan. However, different from other fields, the generation growth rate of science is actually increasing (from 0.938 to 1.036). This may be indicative of the growing demand in Taiwan's high-tech industry. Second, according to the two policy experiments in Tables A3 and A4, we conclude that the main message of our results remains unchanged. That is, a subsidy to domestic doctoral students is more effective in boosting the number of domestic doctoral students than subsidizing professors' research. Third, we find that the effect of subsidizing domestic doctoral students to attract them increases as the generation growth rate decreases. Taking the field of aggregate as an example, the policy reform increases domestic doctoral students by 19.40% when $g = 0.946$, while it only increases by 16.57% in the baseline ($g = 0.999$). However, as we mentioned in the main text, here we also observe that attracting more domestic doctoral students does not necessarily improve the average welfare because of fewer overseas-trained professors and lower knowledge accumulation.

E.2 Tests for the Depreciation Rate of Knowledge

Our setup is proposed by Griliches (1979), which is the pioneering paper to introduce a knowledge capital model and distinguishes the firm-specific knowledge capital from the social research and development knowledge (hereafter, social knowledge). In addition to the depreciation of the firm-specific knowledge capital, Griliches discusses the reasons why the value of social knowledge could decrease over time. For example, the arrival of new products or new technologies may make the knowledge about older products or older technologies redundant. That is, although social knowledge in the society does not disappear per se, the new knowledge may replace the old ones in the production of final goods. Moreover, the constant changes of the environment also render the knowledge about previous environment less relevant over time. For instance, the knowledge of COVID-19 is vital during the pandemic, but less relevant after the pandemic. Because the contribution of old knowledge to final output is decreasing overtime, the paper argues that there are depreciations of both types of knowledge capital.

Previous studies estimate that the annual depreciation rate of the firm-specific knowledge capital is around 12%-29% (see, for example, Hall and Mairesse, 1995; Nadiri and Prucha, 1996; Huang and Diewert, 2011; and Doraszelski and Jaumandreu, 2013). Regarding the social knowledge, as mentioned in Griliches (1979), "the real problem here is our lack of information about the possible rates of such depreciation. The only thing one might be willing to say is that one would expect such social rates of depreciation to be lower than the private ones".

In the main text, we thus follow the literature to set the annual depreciation rate of knowledge at 15%. That is, the depreciation rate in the model is $\delta = 0.728$ in the baseline. Moreover, to address this issue carefully, we conduct robustness tests with lower rates of annual depreciation: 10% (i.e., $\delta = 0.570$) and 5% (i.e., $\delta = 0.337$). Then, the model is re-calibrated and the calibrated result is summarized in Table A5. We find that, due to the calibration strategy, only the values of ϕ_Y and A change when the annual depreciation rate is varying. Besides, the two policy experiments in Tables A6 and A7 are again consistent with our main message: a subsidy to domestic doctoral students is more effective in boosting the number of domestic doctoral students than subsidizing professors' research.

E.3 Tests for the Elasticity of Substitution between Professor and Ph.D. Student

In the model section, knowledge is assumed to be produced by a generalized CES technology, which is constituted by three parameters (ϕ_x, θ_x, and λ). However, in the quantitative analysis, the problem we face is that we lack enough data moments to calibrate all the three parameters. Therefore, we have to make an assumption and set $\theta_x = 0.01$ and $\lambda = 1$ so that we can proceed the calibration. This strategy allows us to calibrate ϕ_x by matching doctoral student's wage (s^*). Besides, the setting implies that our knowledge production technology is approximated to be a Cobb-Douglas function.

We are well noted that, approximating the knowledge production to be a Cobb-Douglas function implies that Ph.D. students are essential in producing knowledge. Indeed, this assumption may not be always true in some fields. In practice, there may not be a strong complementarity between a professor and graduate students, as a professor has the capability to conduct independent research without relying on graduate students. Quantitatively, a stronger complementarity results in the calibrated outcome where $B_1 < B_0$, contradicting the data from Taiwan. Therefore, here we conduct robustness tests by assuming a higher substitutability between professor and Ph.D. student. Specifically, equation (19) implies that the calibrated value of ϕ_x is increasing in θ_x. Since $0 < \phi_x < 1$, there exists an upper limit ($\bar{\theta}_x$) for the setting of θ_x. Taking the calibration in the field of humanities in the baseline economy as an example, $\bar{\theta}_x \approx 0.0558$. Therefore, in the robustness tests, we change θ_x from 0.01 to 0.025 or 0.05 (more substitute) and re-calibrate the model. The calibrated result is summarized in Table A8. Because of the calibration strategy, we find that the values of ϕ_x, B_0, and B_1 alter, while others remain unchanged. In addition, as shown in Tables A9 and A10, our main conclusion still holds even if professor and doctoral student are more substitute in knowledge production. Therefore, we are confident that the Cobb-Douglas technology assumption is not the main driver that leads to our conclusion.

E.4 Tests for the Elasticity of Substitution between Knowledge and Labor

To the best of our knowledge, few studies estimate the elasticity of substitution between knowledge and labor. Lacking a definitive understanding of it, we consequently model the production of final consumption goods in a generalized form, utilizing a CES technology. The CES production in equation (3) consists of three parameters: A, ϕ_Y, and θ_Y. When conducting the quantitative analysis, we encounter the problem that we do not have enough data moments to calibrate all the three parameters. Therefore, we have to make an assumption so that we are able to calibrate the rest two parameters by matching w^* and μ^*. Thus, our calibration strategy is to approximate a Cobb-Douglas function by setting $\theta_Y = 0.01$. Although we assume the value of θ_Y, the production weight (ϕ_Y) and the TFP (A) are still flexible to match data in the calibration. This is consistent with our idea that modeling the production technology in a generalized manner.

To test if the setting of θ_Y is essential to our result, we change θ_Y to be 0.5 or -0.5 so that knowledge and labor become more substitute or compliment in the production. Given a specific value of θ_Y, the model is re-calibrated and the results are provided in Table A11. We observe that ϕ_Y and A absorb the change in θ_Y due to our calibration strategy, while others remain unchanged. Based on the new calibrated results, we proceed to the two policy experiments. As shown in Tables A12 and A13, we find that the policy effects with various θ_Y are similar to that of the baseline. Thus, we conclude that our main message still holds here.

E.5 Tests for the Ratio of Brain Drain

In the model section, the ratio of brain drain, ζ, refers to the proportion of Taiwanese students who pursue doctoral degrees overseas, work in foreign countries, and do not return to Taiwan after completing their studies. However, the data is unavailable in reality. Therefore, we turn to consider the data of international doctoral students in the United State. As we mentioned in Section 3.1, among all doctoral students who study in the United State with temporary visa, there was about 19% of them would stay and work in the United State after graduation. However, the proportion of doctoral students staying and working in the United States may vary with countries where they are from and cultural differences. For example, in 2010, Table 53 of the NCSES survey reported that 74.5% of doctoral students from East Asia and South Asia countries intended to stay in the United States after doctorate receipt, while only 58.5% of doctoral students from Taiwan intended to do so. Hence, the 19% might serve as an average upper limit for Taiwan. Considering the relative intention, the ratio of brain drain is then adjusted to be 15% (=19%*58.5%/74.5%). Thus, we set $\zeta = 15\%$ in the baseline.

To address this issue carefully, we examine three additional scenarios: $\zeta = 16\%$, 17.5%, and varying values across different fields. They are discussed as follows. First, the NCSES survey reported that in 2010 the intention rate of all doctoral students who were temporary visa holders to stay in the United States after graduation was 69.1%. Adjusted by the intention rate of Taiwanese students relative to all temporary visa holders (58.5%/69.1%), the ratio of brain drain is 16%. Second, the data of 2010 may not be viewed as regular because there was a financial crisis from 2008 to 2009. Therefore, we use the average intention rate during 2009-2015 instead. The average intention rate of Taiwanese students was 64.8%, while it was 70.5% for all doctoral students with temporary visa in the United States during 2009-2015. Using the relative intention rate to be the adjustment, the ratio of brain drain becomes 17.5%. Third, Table 51 of the NCSES survey also reported the ratio of brain drain by major field of study. However, the field classification in NCSES survey differs from ours described in Appendix C. To calculate the corresponding brain drain ratios for our fields, we define "all temporary visa holders" in NCSES survey as the field of AGG in our paper, "engineering" to be the field of ENG, "life science" and "physical sciences and earth sciences" subtracted by "health sciences" to be SCI, "health sciences" to be MED, "humanities and arts" to be HUM, and "Psychology and social sciences" to be SOC. Adjusted by the relative intention rate (64.8%/70.5%), the ratios of brain drain are 17.5%, 21.7%, 8.2%, 20.7%, 14.1%, and 16.0% for the fields of AGG, ENG, SCI, MED, HUM, and SOC, respectively.

For all three scenarios, we re-calibrate the model and the results are summarized in Table A14. We find that the effect of varying ζ on calibration is minor. Because more doctoral graduates stay overseas, the probability of finding a faculty position in Taiwan slightly increases, the stock of knowledge declines, and output per labor is lower. Finally, based on the calibrated results, the two policy experiments are conducted to compare with the baseline. As shown in Tables A15 and A16, we still observe that subsidizing domestic doctoral students is more effective in increasing the number of domestic doctoral students than providing a subsidy to professors' research. But the policy effect is slightly weaker when the ratio of brain drain increases. For example, in the field of AGG, subsidizing domestic doctoral students results in an increase in the number of domestic doctoral students by 16.35% when $\zeta = 17.5\%$, while it increases by 16.57% in the baseline setup ($\zeta = 15\%$). We therefore conclude that our main message still holds under varying values of the brain drain ratio.

Table A2: Robustness test for g - parameters and calibration

	Baseline (computing g using the data of 2006-2015)						Lower growth rate of generation (computing g using the data of 2006-2022)					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
g	0.999	0.919	0.938	1.007	1.225	0.981	0.946	0.883	1.036	0.974	1.053	0.902
Parameters by fields												
b	0.763	0.833	0.777	0.754	0.657	0.691	0.763	0.833	0.777	0.754	0.657	0.691
α	1.169	1.247	1.309	1.204	1.091	1.019	1.169	1.247	1.309	1.204	1.091	1.019
v_1	0.109	-0.135	-0.051	0.242	0.084	-0.340	0.110	-0.126	-0.065	0.242	0.045	-0.326
a	32.487	30.825	26.831	25.079	34.138	41.438	32.487	30.825	26.831	25.079	34.138	41.438
$\bar{d}$	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585
ϕ_x	0.144	0.015	0.034	0.081	0.895	0.030	0.106	0.011	0.065	0.066	0.226	0.017
B_0	1.034	1.032	1.029	1.031	1.225	1.024	1.032	1.032	1.030	1.031	1.025	1.024
B_1	1.037	1.036	1.032	1.032	1.227	1.028	1.035	1.036	1.033	1.031	1.027	1.027
ϕ_Y	0.970	0.841	0.910	0.931	0.978	0.965	0.967	0.802	0.934	0.925	0.977	0.954
A	5.606	9.010	7.421	6.906	4.768	5.786	5.665	10.181	6.856	7.063	4.812	6.055
κ	1.038	1.038	1.031	1.014	1.016	1.014	1.038	1.038	1.031	1.014	1.016	1.014
Calibrated result												
ε^*	0.017	0.024	0.023	0.028	0.012	0.008	0.017	0.024	0.023	0.028	0.012	0.008
μ^*	0.039	0.056	0.055	0.068	0.028	0.020	0.039	0.056	0.055	0.068	0.028	0.020
q_0^*	0.748	0.806	0.754	0.727	0.649	0.684	0.748	0.806	0.754	0.727	0.649	0.684
q_1^*	0.758	0.825	0.770	0.746	0.655	0.689	0.758	0.825	0.770	0.746	0.655	0.689
m_0^*	0.655	0.813	0.735	0.962	0.499	0.420	0.655	0.813	0.735	0.962	0.499	0.420
m_1^*	0.869	1.247	0.992	1.028	0.615	0.589	0.869	1.247	0.992	1.028	0.615	0.589
p^*	0.259	0.140	0.182	0.201	0.682	0.440	0.226	0.126	0.234	0.185	0.478	0.355
s^*	2.952	2.842	2.916	3.229	2.266	1.733	2.952	2.842	2.916	3.229	2.266	1.733
h_0^*	11.936	152.158	62.296	36.459	0.164	24.344	16.845	222.330	31.923	45.553	3.994	43.873
h_1^*	15.827	233.424	84.065	38.975	0.202	34.092	22.335	341.075	43.078	48.697	4.922	61.440
x_0^*	16.463	22.098	15.444	16.800	5.651	10.093	16.463	22.098	15.444	16.800	5.651	10.093
x_1^*	21.830	33.901	20.841	17.960	6.963	14.134	21.830	33.901	20.841	17.960	6.963	14.134
w^*	5.147	5.959	5.767	5.765	4.408	5.112	5.147	5.959	5.767	5.765	4.408	5.112
k^*	0.161	0.215	0.168	0.197	0.068	0.076	0.146	0.200	0.198	0.186	0.055	0.065
π^*	0.843	6.990	4.173	2.355	0.229	2.484	1.141	10.166	2.206	2.896	0.907	4.419
y^*	5.305	7.067	6.327	6.183	4.503	5.292	5.320	7.410	6.167	6.228	4.508	5.351

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. All common parameters, except for g, share identical values as those listed in Table 1.

Table A3: Robustness test for g - impacts of subsidy to domestic doctoral students

	Baseline (computing g using the data of 2006-2015)						Lower growth rate of generation (computing g using the data of 2006-2022)					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
g	0.999	0.919	0.938	1.007	1.225	0.981	0.946	0.883	1.036	0.974	1.053	0.902
Wage of domestic doctoral student												
s^*	2.469	2.326	2.453	2.898	1.802	1.034	2.422	2.264	2.535	2.875	1.754	0.976
$\bar{s}$	0.490	0.522	0.472	0.340	0.464	0.705	0.537	0.582	0.389	0.364	0.516	0.800
Percentage change relative to the corresponding benchmark economy												
ε^*	-21.68%	-22.13%	-19.44%	-13.86%	-6.06%	-90.48%	-24.99%	-24.89%	-15.29%	-14.91%	-34.21%	-99.88%
$\mu^* - \varepsilon^*$	16.57%	21.19%	18.13%	10.64%	3.44%	64.45%	19.40%	24.26%	14.03%	11.65%	21.88%	75.07%
μ^*	0.51%	3.03%	2.38%	0.37%	-0.54%	-0.50%	0.76%	3.66%	1.74%	0.51%	-1.63%	1.74%
q_0^*	0.13%	0.15%	0.12%	0.14%	0.03%	0.27%	0.15%	0.16%	0.10%	0.15%	0.14%	0.28%
q_1^*	0.14%	0.22%	0.17%	0.15%	0.02%	0.26%	0.16%	0.24%	0.14%	0.16%	0.13%	0.29%
m_0^*	19.75%	26.92%	21.49%	11.08%	3.95%	87.24%	23.20%	30.93%	16.56%	12.14%	25.50%	102.11%
m_1^*	19.75%	26.92%	21.49%	11.08%	3.94%	87.24%	23.20%	30.93%	16.56%	12.14%	25.50%	102.11%
p^*	-0.56%	-2.28%	-1.32%	-0.22%	0.37%	-4.67%	-0.81%	-2.78%	-0.92%	-0.35%	0.59%	-7.24%
$s^* + \bar{s}$	0.24%	0.22%	0.28%	0.27%	0.03%	0.35%	0.22%	0.14%	0.24%	0.29%	0.21%	2.49%
h_0^*	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%	0.86%	4.04%	1.14%	-0.30%	-3.05%	13.06%
h_1^*	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%	0.86%	4.04%	1.14%	-0.30%	-3.05%	13.06%
x_0^*	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%	2.17%	0.28%	0.97%	0.73%	5.15%	1.16%
x_1^*	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%	2.17%	0.28%	0.97%	0.73%	5.15%	1.16%
w^*	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%	-0.03%	-0.97%	-0.08%	0.02%	0.04%	-0.59%
k^*	-0.22%	-4.21%	-2.17%	0.38%	2.92%	-10.64%	-1.02%	-4.88%	-1.25%	0.25%	2.05%	-12.46%
π^*	-2.47%	3.28%	1.33%	-1.24%	-20.07%	9.04%	-1.27%	3.75%	0.18%	-1.02%	-7.75%	11.78%
y^*	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%	-0.03%	-0.97%	-0.08%	0.02%	0.05%	-0.59%
Average lifetime utilities												
U	-0.04%	-0.40%	-0.14%	-0.02%	0.01%	-0.26%	-0.05%	-0.57%	-0.08%	-0.02%	-0.00%	-0.39%
U_I	-0.05%	-0.40%	-0.14%	-0.01%	-0.02%	-0.26%	-0.04%	-0.58%	-0.08%	-0.02%	-0.01%	-0.96%
U_D	-0.03%	-0.35%	-0.10%	0.01%	-0.01%	-0.18%	-0.03%	-0.53%	-0.05%	-0.00%	0.02%	-0.35%
U_W	-0.03%	-0.40%	-0.14%	-0.01%	0.01%	-0.26%	-0.05%	-0.57%	-0.07%	-0.02%	-0.00%	-0.39%

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. All experiments are conducted in the scenario of $\tau = 0.05\%$.

Table A4: Robustness test for g - impacts of subsidy to professors' research

	Baseline (computing g using the data of 2006-2015)						Lower growth rate of generation (computing g using the data of 2006-2022)					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
g	0.999	0.919	0.938	1.007	1.225	0.981	0.946	0.883	1.036	0.974	1.053	0.902
Subsidy to professor												
$\bar{\rho}_h h_0^*$	0.372	0.517	0.410	0.362	0.231	0.487	0.418	0.593	0.326	0.390	0.311	0.590
$\bar{\rho}_h h_1^*$	0.493	0.793	0.553	0.387	0.285	0.681	0.555	0.909	0.440	0.417	0.383	0.826
Percentage change relative to the corresponding benchmark economy												
ε^*	4.22%	0.21%	0.66%	1.05%	39.41%	3.55%	2.71%	0.43%	1.09%	1.40%	9.96%	1.77%
$\mu^* - \varepsilon^*$	-2.83%	-0.31%	-0.63%	-0.89%	-23.44%	-2.13%	-2.18%	-0.31%	-0.95%	-0.89%	-6.25%	-1.28%
μ^*	0.13%	-0.09%	-0.09%	-0.07%	2.90%	0.25%	-0.13%	0.00%	-0.09%	0.07%	0.54%	0.00%
q_0^*	-0.03%	-0.00%	-0.00%	-0.01%	-0.18%	-0.01%	-0.02%	-0.00%	-0.01%	-0.02%	-0.04%	-0.01%
q_1^*	-0.03%	-0.00%	-0.01%	-0.01%	-0.15%	-0.01%	-0.02%	-0.00%	-0.01%	-0.02%	-0.04%	-0.01%
m_0^*	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%	-2.51%	-0.38%	-1.10%	-0.92%	-7.02%	-1.53%
m_1^*	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%	-2.51%	-0.38%	-1.10%	-0.92%	-7.02%	-1.53%
p^*	-0.11%	0.08%	0.06%	0.06%	-1.70%	-0.05%	0.13%	-0.01%	0.04%	-0.08%	-0.24%	0.11%
s^*	0.10%	-0.02%	-0.01%	-0.04%	-1.28%	0.18%	-0.08%	0.05%	-0.02%	0.07%	-0.04%	-0.05%
$(1+\bar{\rho}_h)h_0^*$	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%	-0.08%	-0.06%	-0.08%	0.01%	0.80%	-0.22%
$(1+\bar{\rho}_h)h_1^*$	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%	-0.08%	-0.06%	-0.08%	0.01%	0.80%	-0.22%
x_0^*	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%	-0.26%	-0.00%	-0.07%	-0.06%	-1.59%	-0.03%
x_1^*	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%	-0.26%	-0.00%	-0.07%	-0.06%	-1.59%	-0.03%
w^*	0.00%	0.01%	0.01%	-0.00%	-0.47%	0.01%	0.00%	0.01%	0.01%	-0.00%	-0.02%	0.01%
k^*	0.03%	0.05%	0.07%	-0.04%	-20.43%	0.40%	0.08%	0.08%	0.08%	-0.02%	-0.76%	0.23%
π^*	-2.73%	-0.38%	-0.70%	-0.88%	-4.91%	-2.31%	-2.32%	-0.32%	-1.03%	-0.79%	-5.49%	-1.54%
y^*	0.00%	0.01%	0.01%	-0.00%	-0.48%	0.01%	0.00%	0.01%	0.01%	-0.00%	-0.02%	0.01%
Average lifetime utilities												
U	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%	-0.03%	-0.02%	-0.03%	-0.03%	-0.04%	-0.02%
U_I	-0.05%	-0.00%	-0.01%	-0.01%	0.02%	-0.07%	-0.01%	-0.02%	-0.02%	-0.04%	-0.04%	-0.01%
U_D	-0.03%	-0.02%	-0.02%	-0.03%	-0.37%	-0.04%	-0.04%	-0.02%	-0.03%	-0.03%	-0.06%	-0.03%
U_W	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%	-0.03%	-0.02%	-0.03%	-0.03%	-0.05%	-0.02%

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. All experiments are conducted in the scenario of $\tau = 0.05\%$.

Table A5: Robustness test for δ - parameters and calibration

	Annual depreciation rate = 15% (baseline)						Annual depreciation rate = 10%						Annual depreciation rate = 5%					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
δ	0.728	0.728	0.728	0.728	0.728	0.728	0.570	0.570	0.570	0.570	0.570	0.570	0.337	0.337	0.337	0.337	0.337	0.337
Parameters by fields																		
b	0.763	0.833	0.777	0.754	0.657	0.691	0.763	0.833	0.777	0.754	0.657	0.691	0.763	0.833	0.777	0.754	0.657	0.691
α	1.169	1.247	1.309	1.204	1.091	1.019	1.169	1.247	1.309	1.204	1.091	1.019	1.169	1.247	1.309	1.204	1.091	1.019
v_1	0.109	-0.135	-0.051	0.242	0.084	-0.340	0.109	-0.135	-0.051	0.242	0.084	-0.340	0.109	-0.135	-0.051	0.242	0.084	-0.340
a	32.487	30.825	26.831	25.079	34.138	41.438	32.487	30.825	26.831	25.079	34.138	41.438	32.487	30.825	26.831	25.079	34.138	41.438
g	0.999	0.919	0.938	1.007	1.225	0.981	0.999	0.919	0.938	1.007	1.225	0.981	0.999	0.919	0.938	1.007	1.225	0.981
$\bar{d}$	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585
ϕ_x	0.144	0.015	0.034	0.081	0.895	0.030	0.144	0.015	0.034	0.081	0.895	0.030	0.144	0.015	0.034	0.081	0.895	0.030
B_0	1.034	1.032	1.029	1.031	1.225	1.024	1.034	1.032	1.029	1.031	1.225	1.024	1.034	1.032	1.029	1.031	1.225	1.024
B_1	1.037	1.036	1.032	1.032	1.227	1.028	1.037	1.036	1.032	1.032	1.227	1.028	1.037	1.036	1.032	1.032	1.227	1.028
ϕ_Y	0.970	0.841	0.910	0.931	0.978	0.965	0.970	0.842	0.910	0.932	0.978	0.965	0.970	0.842	0.911	0.932	0.979	0.965
A	5.606	9.010	7.421	6.906	4.768	5.786	5.564	8.618	7.243	6.792	4.749	5.736	5.476	7.779	6.855	6.557	4.714	5.627
κ	1.038	1.038	1.031	1.014	1.016	1.014	1.038	1.038	1.031	1.014	1.016	1.014	1.038	1.038	1.031	1.014	1.016	1.014
Calibrated result																		
ε^*	0.017	0.024	0.023	0.028	0.012	0.008	0.017	0.024	0.023	0.028	0.012	0.008	0.017	0.024	0.023	0.028	0.012	0.008
μ^*	0.039	0.056	0.055	0.068	0.028	0.020	0.039	0.056	0.055	0.068	0.028	0.020	0.039	0.056	0.055	0.068	0.028	0.020
q_0^*	0.748	0.806	0.754	0.727	0.649	0.684	0.748	0.806	0.754	0.727	0.649	0.684	0.748	0.806	0.754	0.727	0.649	0.684
q_1^*	0.758	0.825	0.770	0.746	0.655	0.689	0.758	0.825	0.770	0.746	0.655	0.689	0.758	0.825	0.770	0.746	0.655	0.689
m_0^*	0.655	0.813	0.735	0.962	0.499	0.420	0.655	0.813	0.735	0.962	0.499	0.420	0.655	0.813	0.735	0.962	0.499	0.420
m_1^*	0.869	1.247	0.992	1.028	0.615	0.589	0.869	1.247	0.992	1.028	0.615	0.589	0.869	1.247	0.992	1.028	0.615	0.589
p^*	0.259	0.140	0.182	0.201	0.682	0.440	0.259	0.140	0.182	0.201	0.682	0.440	0.259	0.140	0.182	0.201	0.682	0.440
s^*	2.952	2.842	2.916	3.229	2.266	1.733	2.952	2.842	2.916	3.229	2.266	1.733	2.952	2.842	2.916	3.229	2.266	1.733
h_0^*	11.936	152.158	62.296	36.459	0.164	24.344	11.936	152.158	62.296	36.459	0.164	24.344	11.936	152.158	62.296	36.459	0.164	24.344
h_1^*	15.827	233.424	84.065	38.975	0.202	34.092	15.827	233.424	84.065	38.975	0.202	34.092	15.827	233.424	84.065	38.975	0.202	34.092
x_0^*	16.463	22.098	15.444	16.800	5.651	10.093	16.463	22.098	15.444	16.800	5.651	10.093	16.463	22.098	15.444	16.800	5.651	10.093
x_1^*	21.830	33.901	20.841	17.960	6.963	14.134	21.830	33.901	20.841	17.960	6.963	14.134	21.830	33.901	20.841	17.960	6.963	14.134
w^*	5.147	5.959	5.767	5.765	4.408	5.112	5.147	5.959	5.767	5.765	4.408	5.112	5.147	5.959	5.767	5.765	4.408	5.112
k^*	0.161	0.215	0.168	0.197	0.068	0.076	0.205	0.284	0.220	0.251	0.082	0.097	0.348	0.543	0.406	0.420	0.116	0.169
π^*	0.843	6.990	4.173	2.355	0.229	2.484	0.843	6.990	4.173	2.355	0.229	2.484	0.843	6.990	4.173	2.355	0.229	2.484
y^*	5.305	7.067	6.327	6.183	4.503	5.292	5.305	7.067	6.327	6.183	4.503	5.292	5.305	7.067	6.327	6.183	4.503	5.292

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. All common parameters, except for δ, share identical values as those listed in Table 1.

Table A6: Robustness test for δ - impacts of subsidy to domestic doctoral students

	Annual depreciation rate = 15% (baseline)						Annual depreciation rate = 10%						Annual depreciation rate = 5%					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
δ	0.728	0.728	0.728	0.728	0.728	0.728	0.570	0.570	0.570	0.570	0.570	0.570	0.337	0.337	0.337	0.337	0.337	0.337
Wage of domestic doctoral student																		
s^*	2.469	2.326	2.453	2.898	1.802	1.034	2.469	2.326	2.453	2.898	1.802	1.034	2.469	2.326	2.453	2.898	1.802	1.034
$\bar{s}$	0.490	0.522	0.472	0.340	0.464	0.705	0.490	0.522	0.472	0.340	0.464	0.705	0.490	0.522	0.472	0.340	0.464	0.705
Percentage change relative to the corresponding benchmark economy																		
ε^*	-21.68%	-22.13%	-19.44%	-13.86%	-6.06%	-90.48%	-21.68%	-22.13%	-19.44%	-13.86%	-6.06%	-90.48%	-21.68%	-22.13%	-19.44%	-13.86%	-6.06%	-90.48%
$\mu^* - \varepsilon^*$	16.57%	21.19%	18.13%	10.64%	3.44%	64.45%	16.57%	21.19%	18.13%	10.64%	3.44%	64.45%	16.57%	21.19%	18.13%	10.64%	3.44%	64.45%
μ^*	0.51%	3.03%	2.38%	0.37%	-0.54%	-0.50%	0.51%	3.03%	2.38%	0.37%	-0.54%	-0.50%	0.51%	3.03%	2.38%	0.37%	-0.54%	-0.50%
q_0^*	0.13%	0.15%	0.12%	0.14%	0.03%	0.27%	0.13%	0.15%	0.12%	0.14%	0.03%	0.27%	0.13%	0.15%	0.12%	0.14%	0.03%	0.27%
q_1^*	0.14%	0.22%	0.17%	0.15%	0.02%	0.26%	0.14%	0.22%	0.17%	0.15%	0.02%	0.26%	0.14%	0.22%	0.17%	0.15%	0.02%	0.26%
m_0^*	19.75%	26.92%	21.49%	11.08%	3.95%	87.24%	19.75%	26.92%	21.49%	11.08%	3.95%	87.24%	19.75%	26.92%	21.49%	11.08%	3.95%	87.24%
m_1^*	19.75%	26.92%	21.49%	11.08%	3.94%	87.24%	19.75%	26.92%	21.49%	11.08%	3.94%	87.24%	19.75%	26.92%	21.49%	11.08%	3.94%	87.24%
p^*	-0.56%	-2.28%	-1.32%	-0.22%	0.37%	-4.67%	-0.56%	-2.28%	-1.32%	-0.22%	0.37%	-4.67%	-0.56%	-2.28%	-1.32%	-0.22%	0.37%	-4.67%
$s^* + \bar{s}$	0.24%	0.22%	0.28%	0.27%	0.03%	0.35%	0.24%	0.22%	0.28%	0.27%	0.03%	0.35%	0.24%	0.22%	0.28%	0.27%	0.03%	0.35%
h_0^*	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%
h_1^*	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%
x_0^*	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%
x_1^*	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%
w^*	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%
k^*	-0.22%	-4.21%	-2.17%	0.38%	2.92%	-10.64%	-0.22%	-4.21%	-2.17%	0.38%	2.92%	-10.64%	-0.22%	-4.21%	-2.17%	0.38%	2.92%	-10.64%
π^*	-2.47%	3.28%	1.33%	-1.24%	-20.07%	9.04%	-2.47%	3.28%	1.33%	-1.24%	-20.07%	9.04%	-2.47%	3.28%	1.33%	-1.24%	-20.07%	9.04%
y^*	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%
Average lifetime utilities																		
U	-0.04%	-0.40%	-0.14%	-0.02%	0.01%	-0.26%	-0.04%	-0.40%	-0.14%	-0.02%	0.01%	-0.26%	-0.04%	-0.40%	-0.14%	-0.02%	0.01%	-0.26%
U_I	-0.05%	-0.40%	-0.14%	-0.01%	-0.02%	-0.26%	-0.05%	-0.40%	-0.14%	-0.01%	-0.02%	-0.26%	-0.05%	-0.40%	-0.14%	-0.01%	-0.02%	-0.26%
U_D	-0.03%	-0.35%	-0.10%	0.01%	-0.01%	-0.18%	-0.03%	-0.35%	-0.10%	0.01%	-0.01%	-0.18%	-0.03%	-0.35%	-0.10%	0.01%	-0.01%	-0.18%
U_W	-0.03%	-0.40%	-0.14%	-0.01%	0.01%	-0.26%	-0.03%	-0.40%	-0.14%	-0.01%	0.01%	-0.26%	-0.03%	-0.40%	-0.14%	-0.01%	0.01%	-0.26%

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. All experiments are conducted in the scenario of $\tau = 0.05\%$.

Table A7: Robustness test for δ - impacts of subsidy to professors' research

	Annual depreciation rate = 15% (baseline)						Annual depreciation rate = 10%						Annual depreciation rate = 5%					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
δ	0.728	0.728	0.728	0.728	0.728	0.728	0.570	0.570	0.570	0.570	0.570	0.570	0.337	0.337	0.337	0.337	0.337	0.337
Subsidy to professor																		
$\bar{\rho}_h h_0^*$	0.372	0.517	0.410	0.362	0.231	0.487	0.372	0.517	0.410	0.362	0.231	0.487	0.372	0.517	0.410	0.362	0.231	0.487
$\bar{\rho}_h h_1^*$	0.493	0.793	0.553	0.387	0.285	0.681	0.493	0.793	0.553	0.387	0.285	0.681	0.493	0.793	0.553	0.387	0.285	0.681
Percentage change relative to the corresponding benchmark economy																		
ε^*	4.22%	0.21%	0.66%	1.05%	39.41%	3.55%	4.22%	0.21%	0.66%	1.05%	39.41%	3.55%	4.22%	0.21%	0.66%	1.05%	39.41%	3.55%
$\mu^* - \varepsilon^*$	-2.83%	-0.31%	-0.63%	-0.89%	-23.44%	-2.13%	-2.83%	-0.31%	-0.63%	-0.89%	-23.44%	-2.13%	-2.83%	-0.31%	-0.63%	-0.89%	-23.44%	-2.13%
μ^*	0.13%	-0.09%	-0.09%	-0.07%	2.90%	0.25%	0.13%	-0.09%	-0.09%	-0.07%	2.90%	0.25%	0.13%	-0.09%	-0.09%	-0.07%	2.90%	0.25%
q_0^*	-0.03%	-0.00%	-0.00%	-0.01%	-0.18%	-0.01%	-0.03%	-0.00%	-0.00%	-0.01%	-0.18%	-0.01%	-0.03%	-0.00%	-0.00%	-0.01%	-0.18%	-0.01%
q_1^*	-0.03%	-0.00%	-0.01%	-0.01%	-0.15%	-0.01%	-0.03%	-0.00%	-0.01%	-0.01%	-0.15%	-0.01%	-0.03%	-0.00%	-0.01%	-0.01%	-0.15%	-0.01%
m_0^*	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%
m_1^*	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%
p^*	-0.11%	0.08%	0.06%	0.06%	-1.70%	-0.05%	-0.11%	0.08%	0.06%	0.06%	-1.70%	-0.05%	-0.11%	0.08%	0.06%	0.06%	-1.70%	-0.05%
s^*	0.10%	-0.02%	-0.01%	-0.04%	-1.28%	0.18%	0.10%	-0.02%	-0.01%	-0.04%	-1.28%	0.18%	0.10%	-0.02%	-0.01%	-0.04%	-1.28%	0.18%
$(1+\bar{\rho}_h)h_0^*$	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%
$(1+\bar{\rho}_h)h_1^*$	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%
x_0^*	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%
x_1^*	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%
w^*	0.00%	0.01%	0.01%	-0.00%	-0.47%	0.01%	0.00%	0.01%	0.01%	-0.00%	-0.47%	0.01%	0.00%	0.01%	0.01%	-0.00%	-0.47%	0.01%
k^*	0.03%	0.05%	0.07%	-0.04%	-20.43%	0.40%	0.03%	0.05%	0.07%	-0.04%	-20.43%	0.40%	0.03%	0.05%	0.07%	-0.04%	-20.43%	0.40%
π^*	-2.73%	-0.38%	-0.70%	-0.88%	-4.91%	-2.31%	-2.73%	-0.38%	-0.70%	-0.88%	-4.91%	-2.31%	-2.73%	-0.38%	-0.70%	-0.88%	-4.91%	-2.31%
y^*	0.00%	0.01%	0.01%	-0.00%	-0.48%	0.01%	0.00%	0.01%	0.01%	-0.00%	-0.48%	0.01%	0.00%	0.01%	0.01%	-0.00%	-0.48%	0.01%
Average lifetime utilities																		
U	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%
U_I	-0.05%	-0.00%	-0.01%	-0.01%	0.02%	-0.07%	-0.05%	-0.00%	-0.01%	-0.01%	0.02%	-0.07%	-0.05%	-0.00%	-0.01%	-0.01%	0.02%	-0.07%
U_D	-0.03%	-0.02%	-0.02%	-0.03%	-0.37%	-0.04%	-0.03%	-0.02%	-0.02%	-0.03%	-0.37%	-0.04%	-0.03%	-0.02%	-0.02%	-0.03%	-0.37%	-0.04%
U_W	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. All experiments are conducted in the scenario of $\tau = 0.05\%$.

Table A8: Robustness test for θ_x - parameters and calibration

	$\theta_x = 0.01$ (baseline)						$\theta_x = 0.025$						$\theta_x = 0.05$					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
Parameters by fields																		
b	0.763	0.833	0.777	0.754	0.657	0.691	0.763	0.833	0.777	0.754	0.657	0.691	0.763	0.833	0.777	0.754	0.657	0.691
α	1.169	1.247	1.309	1.204	1.091	1.019	1.169	1.247	1.309	1.204	1.091	1.019	1.169	1.247	1.309	1.204	1.091	1.019
v_1	0.109	-0.135	-0.051	0.242	0.084	-0.340	0.109	-0.135	-0.051	0.242	0.084	-0.340	0.109	-0.135	-0.051	0.242	0.084	-0.340
a	32.487	30.825	26.831	25.079	34.138	41.438	32.487	30.825	26.831	25.079	34.138	41.438	32.487	30.825	26.831	25.079	34.138	41.438
g	0.999	0.919	0.938	1.007	1.225	0.981	0.999	0.919	0.938	1.007	1.225	0.981	0.999	0.919	0.938	1.007	1.225	0.981
$\bar{d}$	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585
ϕ_x	0.144	0.015	0.034	0.081	0.895	0.030	0.151	0.016	0.036	0.084	0.928	0.031	0.164	0.018	0.039	0.091	0.986	0.034
B_0	1.034	1.032	1.029	1.031	1.225	1.024	1.087	1.082	1.074	1.080	1.836	1.062	1.184	1.171	1.153	1.167	9.844	1.128
B_1	1.037	1.036	1.032	1.032	1.227	1.028	1.095	1.094	1.082	1.082	1.845	1.071	1.201	1.196	1.171	1.171	9.947	1.148
ϕ_Y	0.970	0.841	0.910	0.931	0.978	0.965	0.970	0.841	0.910	0.931	0.978	0.965	0.970	0.841	0.910	0.931	0.978	0.965
A	5.606	9.010	7.421	6.906	4.768	5.786	5.606	9.010	7.421	6.906	4.768	5.786	5.606	9.010	7.421	6.906	4.768	5.786
κ	1.038	1.038	1.031	1.014	1.016	1.014	1.038	1.038	1.031	1.014	1.016	1.014	1.038	1.038	1.031	1.014	1.016	1.014
Calibrated result																		
ε^*	0.017	0.024	0.023	0.028	0.012	0.008	0.017	0.024	0.023	0.028	0.012	0.008	0.017	0.024	0.023	0.028	0.012	0.008
μ^*	0.039	0.056	0.055	0.068	0.028	0.020	0.039	0.056	0.055	0.068	0.028	0.020	0.039	0.056	0.055	0.068	0.028	0.020
q_0^*	0.748	0.806	0.754	0.727	0.649	0.684	0.748	0.806	0.754	0.727	0.649	0.684	0.748	0.806	0.754	0.727	0.649	0.684
q_1^*	0.758	0.825	0.770	0.746	0.655	0.689	0.758	0.825	0.770	0.746	0.655	0.689	0.758	0.825	0.770	0.746	0.655	0.689
m_0^*	0.655	0.813	0.735	0.962	0.499	0.420	0.655	0.813	0.735	0.962	0.499	0.420	0.655	0.813	0.735	0.962	0.499	0.420
m_1^*	0.869	1.247	0.992	1.028	0.615	0.589	0.869	1.247	0.992	1.028	0.615	0.589	0.869	1.247	0.992	1.028	0.615	0.589
p^*	0.259	0.140	0.182	0.201	0.682	0.440	0.259	0.140	0.182	0.201	0.682	0.440	0.259	0.140	0.182	0.201	0.682	0.440
s^*	2.952	2.842	2.916	3.229	2.266	1.733	2.952	2.842	2.916	3.229	2.266	1.733	2.952	2.842	2.916	3.229	2.266	1.733
h_0^*	11.936	152.158	62.296	36.459	0.164	24.344	11.936	152.158	62.296	36.459	0.164	24.344	11.936	152.158	62.296	36.459	0.164	24.344
h_1^*	15.827	233.424	84.065	38.975	0.202	34.092	15.827	233.424	84.065	38.975	0.202	34.092	15.827	233.424	84.065	38.975	0.202	34.092
x_0^*	16.463	22.098	15.444	16.800	5.651	10.093	16.463	22.098	15.444	16.800	5.651	10.093	16.463	22.098	15.444	16.800	5.651	10.093
x_1^*	21.830	33.901	20.841	17.960	6.963	14.134	21.830	33.901	20.841	17.960	6.963	14.134	21.830	33.901	20.841	17.960	6.963	14.134
w^*	5.147	5.959	5.767	5.765	4.408	5.112	5.147	5.959	5.767	5.765	4.408	5.112	5.147	5.959	5.767	5.765	4.408	5.112
k^*	0.161	0.215	0.168	0.197	0.068	0.076	0.161	0.215	0.168	0.197	0.068	0.076	0.161	0.215	0.168	0.197	0.068	0.076
π^*	0.843	6.990	4.173	2.355	0.229	2.484	0.843	6.990	4.173	2.355	0.229	2.484	0.843	6.990	4.173	2.355	0.229	2.484
y^*	5.305	7.067	6.327	6.183	4.503	5.292	5.305	7.067	6.327	6.183	4.503	5.292	5.305	7.067	6.327	6.183	4.503	5.292

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. All common parameters, except for θ_x, share identical values as those listed in Table 1.

Table A9: Robustness test for θ_x - impacts of subsidy to domestic doctoral students

	$\theta_x = 0.01$ (baseline)						$\theta_x = 0.025$						$\theta_x = 0.05$					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
Wage of domestic doctoral student																		
s^*	2.469	2.326	2.453	2.898	1.802	1.034	2.471	2.326	2.453	2.899	1.802	1.038	2.472	2.331	2.456	2.900	1.803	1.044
$\bar{s}$	0.490	0.522	0.472	0.340	0.464	0.705	0.489	0.520	0.471	0.340	0.464	0.701	0.487	0.518	0.469	0.339	0.464	0.694
Percentage change relative to the corresponding benchmark economy																		
ε^*	-21.68%	-22.13%	-19.44%	-13.86%	-6.06%	-90.48%	-21.98%	-22.77%	-19.66%	-13.86%	-6.06%	-91.07%	-22.89%	-22.98%	-20.31%	-14.21%	-6.06%	-94.03%
$\mu^* - \varepsilon^*$	16.57%	21.19%	18.13%	10.64%	3.44%	64.45%	16.78%	21.65%	18.44%	10.76%	3.44%	65.30%	17.22%	22.11%	18.92%	11.02%	3.44%	67.01%
μ^*	0.51%	3.03%	2.38%	0.37%	-0.54%	-0.50%	0.51%	3.03%	2.47%	0.44%	-0.54%	-0.25%	0.38%	3.21%	2.47%	0.44%	-0.54%	-0.50%
q_0^*	0.13%	0.15%	0.12%	0.14%	0.03%	0.27%	0.13%	0.15%	0.12%	0.14%	0.03%	0.27%	0.14%	0.15%	0.13%	0.14%	0.03%	0.28%
q_1^*	0.14%	0.22%	0.17%	0.15%	0.02%	0.26%	0.14%	0.22%	0.17%	0.15%	0.02%	0.27%	0.14%	0.22%	0.18%	0.15%	0.02%	0.27%
m_0^*	19.75%	26.92%	21.49%	11.08%	3.95%	87.24%	20.02%	27.55%	21.87%	11.21%	3.95%	88.39%	20.59%	28.12%	22.46%	11.48%	3.95%	91.15%
m_1^*	19.75%	26.92%	21.49%	11.08%	3.94%	87.24%	20.02%	27.55%	21.87%	11.21%	3.94%	88.39%	20.59%	28.12%	22.46%	11.48%	3.94%	91.15%
p^*	-0.56%	-2.28%	-1.32%	-0.22%	0.37%	-4.67%	-0.56%	-2.27%	-1.40%	-0.29%	0.37%	-4.93%	-0.44%	-2.43%	-1.37%	-0.29%	0.37%	-4.86%
$s^* + \bar{s}$	0.24%	0.22%	0.28%	0.27%	0.03%	0.35%	0.25%	0.12%	0.25%	0.29%	0.04%	0.38%	0.23%	0.24%	0.27%	0.29%	0.05%	0.31%
h_0^*	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%	-0.01%	3.74%	2.01%	-0.44%	-17.39%	11.09%	0.03%	3.79%	2.07%	-0.45%	-17.46%	11.50%
h_1^*	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%	-0.01%	3.74%	2.01%	-0.44%	-17.39%	11.09%	0.03%	3.79%	2.07%	-0.45%	-17.46%	11.50%
x_0^*	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%	2.58%	0.37%	0.66%	0.84%	3.44%	1.87%	2.66%	0.37%	0.68%	0.86%	3.44%	1.93%
x_1^*	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%	2.58%	0.37%	0.66%	0.84%	3.44%	1.87%	2.66%	0.37%	0.68%	0.86%	3.44%	1.93%
w^*	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%	-0.01%	-0.68%	-0.19%	0.03%	0.06%	-0.38%	-0.01%	-0.69%	-0.20%	0.03%	0.06%	-0.39%
k^*	-0.22%	-4.21%	-2.17%	0.38%	2.92%	-10.64%	-0.23%	-4.32%	-2.20%	0.39%	2.92%	-10.70%	-0.26%	-4.38%	-2.27%	0.40%	2.92%	-11.03%
π^*	-2.47%	3.28%	1.33%	-1.24%	-20.07%	9.04%	-2.46%	3.37%	1.35%	-1.25%	-20.07%	9.10%	-2.43%	3.42%	1.42%	-1.26%	-20.07%	9.49%
y^*	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%	-0.01%	-0.69%	-0.20%	0.03%	0.06%	-0.39%	-0.01%	-0.70%	-0.20%	0.03%	0.06%	-0.40%
Average lifetime utilities																		
U	-0.04%	-0.40%	-0.14%	-0.02%	0.01%	-0.26%	-0.04%	-0.41%	-0.14%	-0.02%	0.01%	-0.27%	-0.04%	-0.42%	-0.14%	-0.02%	0.01%	-0.27%
U_I	-0.05%	-0.40%	-0.14%	-0.01%	-0.02%	-0.26%	-0.05%	-0.40%	-0.15%	-0.02%	-0.02%	-0.32%	-0.03%	-0.43%	-0.14%	-0.02%	-0.02%	-0.27%
U_D	-0.03%	-0.35%	-0.10%	0.01%	-0.01%	-0.18%	-0.02%	-0.37%	-0.12%	0.00%	-0.01%	-0.24%	-0.01%	-0.37%	-0.11%	0.00%	-0.01%	-0.21%
U_W	-0.03%	-0.40%	-0.14%	-0.01%	0.01%	-0.26%	-0.03%	-0.41%	-0.14%	-0.01%	0.01%	-0.26%	-0.04%	-0.42%	-0.14%	-0.01%	0.01%	-0.27%

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. All experiments are conducted in the scenario of $\tau = 0.05\%$.

Table A10: Robustness test for θ_x - impacts of subsidy to professors' research

	$\theta_x = 0.01$ (baseline)						$\theta_x = 0.025$						$\theta_x = 0.05$					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
Subsidy to professor																		
$\bar{\rho}_h h_0^*$	0.372	0.517	0.410	0.362	0.231	0.487	0.372	0.517	0.410	0.362	0.231	0.487	0.372	0.517	0.410	0.362	0.231	0.487
$\bar{\rho}_h h_1^*$	0.493	0.793	0.553	0.387	0.285	0.681	0.493	0.793	0.553	0.387	0.284	0.681	0.493	0.793	0.553	0.387	0.284	0.681
Percentage change relative to the corresponding benchmark economy																		
ε^*	4.22%	0.21%	0.66%	1.05%	39.41%	3.55%	4.22%	0.21%	0.66%	1.58%	40.71%	3.55%	3.91%	0.21%	0.66%	1.58%	40.71%	3.55%
$\mu^* - \varepsilon^*$	-2.83%	-0.31%	-0.63%	-0.89%	-23.44%	-2.13%	-2.83%	-0.31%	-0.63%	-1.01%	-23.75%	-2.13%	-2.83%	-0.31%	-0.63%	-1.01%	-23.75%	-2.13%
μ^*	0.13%	-0.09%	-0.09%	-0.07%	2.90%	0.25%	0.13%	-0.09%	-0.09%	0.07%	3.27%	0.25%	0.00%	-0.09%	-0.09%	0.07%	3.27%	0.25%
q_0^*	-0.03%	-0.00%	-0.00%	-0.01%	-0.18%	-0.01%	-0.03%	-0.00%	-0.00%	-0.02%	-0.18%	-0.01%	-0.02%	-0.00%	-0.00%	-0.02%	-0.18%	-0.01%
q_1^*	-0.03%	-0.00%	-0.01%	-0.01%	-0.15%	-0.01%	-0.03%	-0.00%	-0.01%	-0.02%	-0.15%	-0.01%	-0.02%	-0.00%	-0.01%	-0.02%	-0.15%	-0.01%
m_0^*	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%	-3.31%	-0.36%	-0.73%	-1.06%	-26.13%	-2.59%	-3.29%	-0.36%	-0.73%	-1.06%	-26.13%	-2.59%
m_1^*	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%	-3.31%	-0.36%	-0.73%	-1.06%	-26.13%	-2.59%	-3.29%	-0.36%	-0.73%	-1.06%	-26.13%	-2.59%
p^*	-0.11%	0.08%	0.06%	0.06%	-1.70%	-0.05%	-0.11%	0.08%	0.06%	-0.09%	-2.02%	-0.05%	0.01%	0.08%	0.06%	-0.09%	-2.02%	-0.05%
s^*	0.10%	-0.02%	-0.01%	-0.04%	-1.28%	0.18%	0.05%	-0.03%	-0.02%	0.06%	-1.08%	0.14%	-0.02%	-0.04%	-0.03%	0.04%	-1.17%	0.08%
$(1+\bar{\rho}_h)h_0^*$	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%	-0.06%	-0.04%	-0.07%	0.03%	114.25%	-0.39%	-0.02%	-0.04%	-0.07%	0.03%	114.74%	-0.39%
$(1+\bar{\rho}_h)h_1^*$	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%	-0.06%	-0.04%	-0.07%	0.03%	114.25%	-0.39%	-0.02%	-0.04%	-0.07%	0.03%	114.74%	-0.39%
x_0^*	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%	-0.47%	-0.01%	-0.02%	-0.08%	-23.23%	-0.08%	-0.47%	-0.01%	-0.02%	-0.08%	-23.22%	-0.08%
x_1^*	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%	-0.47%	-0.01%	-0.02%	-0.08%	-23.23%	-0.08%	-0.47%	-0.01%	-0.02%	-0.08%	-23.22%	-0.08%
w^*	0.00%	0.01%	0.01%	-0.00%	-0.47%	0.01%	0.00%	0.01%	0.01%	-0.00%	-0.48%	0.01%	0.00%	0.01%	0.01%	-0.00%	-0.48%	0.01%
k^*	0.03%	0.05%	0.07%	-0.04%	-20.43%	0.40%	0.03%	0.05%	0.07%	-0.03%	-20.70%	0.40%	0.01%	0.05%	0.07%	-0.03%	-20.69%	0.40%
π^*	-2.73%	-0.38%	-0.70%	-0.88%	-4.91%	-2.31%	-2.73%	-0.38%	-0.70%	-0.89%	-4.72%	-2.31%	-2.71%	-0.38%	-0.70%	-0.89%	-4.73%	-2.31%
y^*	0.00%	0.01%	0.01%	-0.00%	-0.48%	0.01%	0.00%	0.01%	0.01%	-0.00%	-0.49%	0.01%	0.00%	0.01%	0.01%	-0.00%	-0.49%	0.01%
Average lifetime utilities																		
U	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%
U_I	-0.05%	-0.00%	-0.01%	-0.01%	0.02%	-0.07%	-0.05%	-0.00%	-0.01%	-0.04%	-0.04%	-0.07%	-0.03%	-0.00%	-0.01%	-0.04%	-0.04%	-0.07%
U_D	-0.03%	-0.02%	-0.02%	-0.03%	-0.37%	-0.04%	-0.04%	-0.02%	-0.03%	-0.03%	-0.38%	-0.04%	-0.04%	-0.02%	-0.03%	-0.03%	-0.40%	-0.06%
U_W	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%	-0.03%	-0.02%	-0.02%	-0.03%	-0.36%	-0.02%	-0.03%	-0.02%	-0.02%	-0.03%	-0.36%	-0.02%

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. All experiments are conducted in the scenario of $\tau = 0.05\%$.

Table A11: Robustness test for θ_Y - parameters and calibration

	θ_Y = -0.5						θ_Y = 0.01 (baseline)						θ_Y = 0.5					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
Parameters by fields																		
b	0.763	0.833	0.777	0.754	0.657	0.691	0.763	0.833	0.777	0.754	0.657	0.691	0.763	0.833	0.777	0.754	0.657	0.691
α	1.169	1.247	1.309	1.204	1.091	1.019	1.169	1.247	1.309	1.204	1.091	1.019	1.169	1.247	1.309	1.204	1.091	1.019
v_1	0.109	-0.135	-0.051	0.242	0.084	-0.340	0.109	-0.135	-0.051	0.242	0.084	-0.340	0.109	-0.135	-0.051	0.242	0.084	-0.340
a	32.487	30.825	26.831	25.079	34.138	41.438	32.487	30.825	26.831	25.079	34.138	41.438	32.487	30.825	26.831	25.079	34.138	41.438
g	0.999	0.919	0.938	1.007	1.225	0.981	0.999	0.919	0.938	1.007	1.225	0.981	0.999	0.919	0.938	1.007	1.225	0.981
$\bar{d}$	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585
ϕ_x	0.144	0.015	0.034	0.081	0.895	0.030	0.144	0.015	0.034	0.081	0.895	0.030	0.144	0.015	0.034	0.081	0.895	0.030
B_0	1.034	1.032	1.029	1.031	1.225	1.024	1.034	1.032	1.029	1.031	1.225	1.024	1.034	1.032	1.029	1.031	1.225	1.024
B_1	1.037	1.036	1.032	1.032	1.227	1.028	1.037	1.036	1.032	1.032	1.227	1.028	1.037	1.036	1.032	1.032	1.227	1.028
ϕ_Y	0.988	0.921	0.962	0.969	0.994	0.990	0.970	0.841	0.910	0.931	0.978	0.965	0.929	0.714	0.808	0.860	0.924	0.886
A	5.500	8.425	7.045	6.675	4.646	5.564	5.606	9.010	7.421	6.906	4.768	5.786	5.789	9.868	8.047	7.275	5.053	6.288
κ	1.038	1.038	1.031	1.014	1.016	1.014	1.038	1.038	1.031	1.014	1.016	1.014	1.038	1.038	1.031	1.014	1.016	1.014
Calibrated result																		
ε^*	0.017	0.024	0.023	0.028	0.012	0.008	0.017	0.024	0.023	0.028	0.012	0.008	0.017	0.024	0.023	0.028	0.012	0.008
μ^*	0.039	0.056	0.055	0.068	0.028	0.020	0.039	0.056	0.055	0.068	0.028	0.020	0.039	0.056	0.055	0.068	0.028	0.020
q_0^*	0.748	0.806	0.754	0.727	0.649	0.684	0.748	0.806	0.754	0.727	0.649	0.684	0.748	0.806	0.754	0.727	0.649	0.684
q_1^*	0.758	0.825	0.770	0.746	0.655	0.689	0.758	0.825	0.770	0.746	0.655	0.689	0.758	0.825	0.770	0.746	0.655	0.689
m_0^*	0.655	0.813	0.735	0.962	0.499	0.420	0.655	0.813	0.735	0.962	0.499	0.420	0.655	0.813	0.735	0.962	0.499	0.420
m_1^*	0.869	1.247	0.992	1.028	0.615	0.589	0.869	1.247	0.992	1.028	0.615	0.589	0.869	1.247	0.992	1.028	0.615	0.589
p^*	0.259	0.140	0.182	0.201	0.682	0.440	0.259	0.140	0.182	0.201	0.682	0.440	0.259	0.140	0.182	0.201	0.682	0.440
s^*	2.952	2.842	2.916	3.229	2.266	1.733	2.952	2.842	2.916	3.229	2.266	1.733	2.952	2.842	2.916	3.229	2.266	1.733
h_0^*	11.936	152.158	62.296	36.459	0.164	24.344	11.936	152.158	62.296	36.459	0.164	24.344	11.936	152.158	62.296	36.459	0.164	24.344
h_1^*	15.827	233.424	84.065	38.975	0.202	34.092	15.827	233.424	84.065	38.975	0.202	34.092	15.827	233.424	84.065	38.975	0.202	34.092
x_0^*	16.463	22.098	15.444	16.800	5.651	10.093	16.463	22.098	15.444	16.800	5.651	10.093	16.463	22.098	15.444	16.800	5.651	10.093
x_1^*	21.830	33.901	20.841	17.960	6.963	14.134	21.830	33.901	20.841	17.960	6.963	14.134	21.830	33.901	20.841	17.960	6.963	14.134
w^*	5.147	5.959	5.767	5.765	4.408	5.112	5.147	5.959	5.767	5.765	4.408	5.112	5.147	5.959	5.767	5.765	4.408	5.112
k^*	0.161	0.215	0.168	0.197	0.068	0.076	0.161	0.215	0.168	0.197	0.068	0.076	0.161	0.215	0.168	0.197	0.068	0.076
π^*	0.843	6.990	4.173	2.355	0.229	2.484	0.843	6.990	4.173	2.355	0.229	2.484	0.843	6.990	4.173	2.355	0.229	2.484
y^*	5.305	7.067	6.327	6.183	4.503	5.292	5.305	7.067	6.327	6.183	4.503	5.292	5.305	7.067	6.327	6.183	4.503	5.292

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. All common parameters, except for θ_Y, share identical values as those listed in Table 1.

Table A12: Robustness test for θ_Y - impacts of subsidy to domestic doctoral students

	θ_Y = -0.5						θ_Y = 0.01 (baseline)						θ_Y = 0.5					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
Wage of domestic doctoral student																		
s^*	2.473	2.332	2.456	2.898	1.792	1.064	2.469	2.326	2.453	2.898	1.802	1.034	2.470	2.320	2.449	2.901	1.772	1.005
$\bar{s}$	0.490	0.513	0.467	0.341	0.477	0.672	0.490	0.522	0.472	0.340	0.464	0.705	0.491	0.530	0.476	0.340	0.486	0.736
Percentage change relative to the corresponding benchmark economy																		
ε^*	-21.38%	-22.34%	-19.66%	-13.51%	-1.30%	-94.03%	-21.68%	-22.13%	-19.44%	-13.86%	-6.06%	-90.48%	-21.68%	-21.91%	-19.22%	-13.33%	-0.43%	-87.53%
$\mu^* - \varepsilon^*$	16.57%	23.34%	19.39%	10.38%	0.63%	72.56%	16.57%	21.19%	18.13%	10.64%	3.44%	64.45%	16.35%	19.35%	17.02%	10.76%	-1.25%	57.62%
μ^*	0.63%	4.19%	3.02%	0.37%	-0.18%	2.73%	0.51%	3.03%	2.38%	0.37%	-0.54%	-0.50%	0.38%	2.05%	1.83%	0.66%	-0.91%	-3.22%
q_0^*	0.13%	0.12%	0.11%	0.14%	0.01%	0.26%	0.13%	0.15%	0.12%	0.14%	0.03%	0.27%	0.13%	0.17%	0.13%	0.13%	0.01%	0.28%
q_1^*	0.14%	0.22%	0.17%	0.14%	0.00%	0.27%	0.14%	0.22%	0.17%	0.15%	0.02%	0.26%	0.14%	0.21%	0.17%	0.14%	0.00%	0.26%
m_0^*	19.72%	29.43%	22.91%	10.82%	0.72%	97.56%	19.75%	26.92%	21.49%	11.08%	3.95%	87.24%	19.52%	24.76%	20.26%	11.20%	-1.29%	78.60%
m_1^*	19.72%	29.43%	22.91%	10.82%	0.72%	97.56%	19.75%	26.92%	21.49%	11.08%	3.94%	87.24%	19.52%	24.76%	20.26%	11.20%	-1.29%	78.60%
p^*	-0.68%	-3.32%	-1.89%	-0.22%	0.14%	-7.83%	-0.56%	-2.28%	-1.32%	-0.22%	0.37%	-4.67%	-0.43%	-1.39%	-0.83%	-0.51%	0.92%	-1.81%
$s^* + \bar{s}$	0.38%	0.08%	0.21%	0.30%	0.16%	0.18%	0.24%	0.22%	0.28%	0.27%	0.03%	0.35%	0.27%	0.30%	0.31%	0.36%	-0.37%	0.45%
h_0^*	0.13%	5.92%	3.28%	-0.66%	-20.32%	20.52%	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%	-0.21%	1.63%	0.80%	-0.22%	-22.80%	2.97%
h_1^*	0.13%	5.92%	3.28%	-0.66%	-20.32%	20.52%	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%	-0.21%	1.63%	0.80%	-0.22%	-22.80%	2.97%
x_0^*	2.54%	0.39%	0.69%	0.81%	0.63%	2.00%	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%	2.52%	0.33%	0.62%	0.84%	-1.13%	1.70%
x_1^*	2.54%	0.39%	0.69%	0.81%	0.63%	2.00%	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%	2.52%	0.33%	0.62%	0.84%	-1.13%	1.70%
w^*	-0.01%	-1.05%	-0.30%	0.04%	0.02%	-0.61%	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%	-0.00%	-0.32%	-0.09%	0.01%	-0.01%	-0.18%
k^*	-0.20%	-4.37%	-2.22%	0.37%	0.53%	-10.98%	-0.22%	-4.21%	-2.17%	0.38%	2.92%	-10.64%	-0.24%	-4.07%	-2.13%	0.40%	-1.10%	-10.34%
π^*	-2.33%	5.52%	2.58%	-1.45%	-20.81%	18.17%	-2.47%	3.28%	1.33%	-1.24%	-20.07%	9.04%	-2.64%	1.30%	0.19%	-1.04%	-21.93%	1.26%
y^*	-0.01%	-0.70%	-0.20%	0.03%	0.01%	-0.41%	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%	-0.01%	-0.64%	-0.19%	0.03%	-0.02%	-0.36%
Average lifetime utilities																		
U	-0.04%	-0.62%	-0.20%	-0.01%	-0.02%	-0.41%	-0.04%	-0.40%	-0.14%	-0.02%	0.01%	-0.26%	-0.03%	-0.21%	-0.08%	-0.02%	-0.04%	-0.14%
U_I	-0.06%	-0.62%	-0.20%	-0.02%	-0.08%	-0.43%	-0.05%	-0.40%	-0.14%	-0.01%	-0.02%	-0.26%	-0.04%	-0.22%	-0.09%	-0.05%	0.03%	-0.15%
U_D	-0.01%	-0.57%	-0.17%	0.00%	-0.04%	-0.36%	-0.03%	-0.35%	-0.10%	0.01%	-0.01%	-0.18%	-0.02%	-0.18%	-0.05%	-0.01%	-0.06%	-0.08%
U_W	-0.04%	-0.62%	-0.20%	-0.01%	-0.02%	-0.41%	-0.03%	-0.40%	-0.14%	-0.01%	0.01%	-0.26%	-0.03%	-0.21%	-0.08%	-0.02%	-0.04%	-0.14%

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. All experiments are conducted in the scenario of $\tau = 0.05\%$.

Table A13: Robustness test for θ_Y - impacts of subsidy to professors' research

	θ_Y = -0.5						θ_Y = 0.01 (baseline)						θ_Y = 0.5					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
Subsidy to professor																		
$\bar{\rho}_h h_0^*$	0.372	0.517	0.410	0.362	0.237	0.487	0.372	0.517	0.410	0.362	0.231	0.487	0.372	0.517	0.410	0.362	0.241	0.487
$\bar{\rho}_h h_1^*$	0.493	0.793	0.553	0.387	0.292	0.682	0.493	0.793	0.553	0.387	0.285	0.681	0.494	0.793	0.553	0.387	0.297	0.682
Percentage change relative to the corresponding benchmark economy																		
ε^*	3.91%	0.64%	1.09%	1.23%	17.32%	2.96%	4.22%	0.21%	0.66%	1.05%	39.41%	3.55%	3.31%	0.43%	0.87%	1.58%	-2.17%	2.96%
$\mu^* - \varepsilon^*$	-2.83%	-0.46%	-0.79%	-0.89%	-4.69%	-2.13%	-2.83%	-0.31%	-0.63%	-0.89%	-23.44%	-2.13%	-2.62%	-0.31%	-0.63%	-1.01%	8.13%	-1.71%
μ^*	0.00%	0.00%	0.00%	0.00%	4.54%	0.00%	0.13%	-0.09%	-0.09%	-0.07%	2.90%	0.25%	-0.13%	0.00%	0.00%	0.07%	3.81%	0.25%
q_0^*	-0.02%	-0.01%	-0.01%	-0.01%	-0.11%	-0.01%	-0.03%	-0.00%	-0.00%	-0.01%	-0.18%	-0.01%	-0.02%	-0.00%	-0.01%	-0.02%	-0.03%	-0.01%
q_1^*	-0.02%	-0.01%	-0.01%	-0.01%	-0.07%	-0.01%	-0.03%	-0.00%	-0.01%	-0.01%	-0.15%	-0.01%	-0.02%	-0.00%	-0.01%	-0.02%	0.01%	-0.01%
m_0^*	-3.29%	-0.58%	-0.93%	-0.92%	-5.71%	-2.54%	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%	-3.02%	-0.38%	-0.74%	-1.06%	8.67%	-2.08%
m_1^*	-3.29%	-0.58%	-0.93%	-0.92%	-5.71%	-2.54%	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%	-3.02%	-0.38%	-0.74%	-1.06%	8.67%	-2.08%
p^*	0.01%	-0.02%	-0.05%	-0.01%	-3.93%	0.18%	-0.11%	0.08%	0.06%	0.06%	-1.70%	-0.05%	0.13%	-0.01%	-0.04%	-0.09%	-3.81%	-0.08%
s^*	0.09%	0.09%	0.09%	-0.03%	0.46%	-0.05%	0.10%	-0.02%	-0.01%	-0.04%	-1.28%	0.18%	-0.12%	0.01%	0.04%	0.06%	0.50%	-0.04%
$(1+\bar{\rho}_h)h_0^*$	-0.05%	-0.14%	-0.17%	0.06%	138.99%	-0.57%	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%	0.01%	-0.03%	-0.04%	0.01%	156.01%	-0.11%
$(1+\bar{\rho}_h)h_1^*$	-0.05%	-0.14%	-0.17%	0.06%	138.99%	-0.57%	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%	0.01%	-0.03%	-0.04%	0.01%	156.01%	-0.11%
x_0^*	-0.47%	-0.01%	-0.03%	-0.07%	-5.00%	-0.07%	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%	-0.43%	-0.01%	-0.02%	-0.08%	7.54%	-0.06%
x_1^*	-0.47%	-0.01%	-0.03%	-0.07%	-5.00%	-0.07%	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%	-0.43%	-0.01%	-0.02%	-0.08%	7.53%	-0.06%
w^*	0.00%	0.03%	0.01%	-0.00%	-0.13%	0.02%	0.00%	0.01%	0.01%	-0.00%	-0.47%	0.01%	-0.00%	0.01%	0.00%	-0.00%	0.07%	0.01%
k^*	0.01%	0.11%	0.11%	-0.03%	-3.92%	0.35%	0.03%	0.05%	0.07%	-0.04%	-20.43%	0.40%	-0.01%	0.07%	0.09%	-0.03%	7.02%	0.33%
π^*	-2.72%	-0.48%	-0.80%	-0.87%	-0.28%	-2.50%	-2.73%	-0.38%	-0.70%	-0.88%	-4.91%	-2.31%	-2.70%	-0.36%	-0.67%	-0.91%	1.55%	-2.05%
y^*	0.00%	0.02%	0.01%	-0.00%	-0.08%	0.01%	0.00%	0.01%	0.01%	-0.00%	-0.48%	0.01%	-0.00%	0.01%	0.01%	-0.00%	0.15%	0.01%
Average lifetime utilities																		
U	-0.03%	-0.01%	-0.02%	-0.03%	-0.12%	-0.02%	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%	-0.03%	-0.02%	-0.03%	-0.03%	0.01%	-0.03%
U_I	-0.03%	-0.02%	-0.04%	-0.02%	-0.15%	-0.03%	-0.05%	-0.00%	-0.01%	-0.01%	0.02%	-0.07%	-0.01%	-0.02%	-0.03%	-0.04%	0.01%	-0.05%
U_D	-0.02%	-0.01%	-0.02%	-0.04%	-0.14%	-0.05%	-0.03%	-0.02%	-0.02%	-0.03%	-0.37%	-0.04%	-0.04%	-0.03%	-0.03%	-0.03%	0.00%	-0.07%
U_W	-0.03%	-0.01%	-0.02%	-0.03%	-0.12%	-0.02%	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%	-0.03%	-0.02%	-0.03%	-0.03%	0.02%	-0.03%

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. All experiments are conducted in the scenario of $\tau = 0.05\%$.

Table A14: Robustness test for ζ - parameters and calibration

	ζ=15% (baseline)						ζ=16%						ζ=17.5%						varying ζ					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
ζ	0.150	0.150	0.150	0.150	0.150	0.150	0.160	0.160	0.160	0.160	0.160	0.160	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.217	0.082	0.207	0.141	0.160
Parameters by fields																								
b	0.763	0.833	0.777	0.754	0.657	0.691	0.763	0.833	0.777	0.754	0.657	0.691	0.763	0.833	0.777	0.754	0.657	0.691	0.763	0.833	0.777	0.754	0.657	0.691
α	1.169	1.247	1.309	1.204	1.091	1.019	1.169	1.247	1.309	1.204	1.091	1.019	1.169	1.247	1.309	1.204	1.091	1.019	1.169	1.247	1.309	1.204	1.091	1.019
v_1	0.109	-0.135	-0.051	0.242	0.084	-0.340	0.110	-0.135	-0.051	0.242	0.085	-0.340	0.110	-0.136	-0.052	0.241	0.086	-0.340	0.110	-0.138	-0.049	0.241	0.083	-0.340
a	32.487	30.825	26.831	25.079	34.138	41.438	32.487	30.825	26.831	25.079	34.138	41.438	32.487	30.825	26.831	25.079	34.138	41.438	32.487	30.825	26.831	25.079	34.138	41.438
g	0.999	0.919	0.938	1.007	1.225	0.981	0.999	0.919	0.938	1.007	1.225	0.981	0.999	0.919	0.938	1.007	1.225	0.981	0.999	0.919	0.938	1.007	1.225	0.981
$\bar{d}$	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585	9.585
ϕ_x	0.144	0.015	0.034	0.081	0.895	0.030	0.146	0.016	0.035	0.082	0.920	0.030	0.148	0.016	0.036	0.083	0.961	0.031	0.148	0.018	0.031	0.087	0.873	0.030
B_0	1.034	1.032	1.029	1.031	1.225	1.024	1.034	1.032	1.029	1.031	1.299	1.024	1.034	1.032	1.029	1.031	1.621	1.024	1.034	1.032	1.029	1.031	1.185	1.024
B_1	1.037	1.036	1.032	1.032	1.227	1.028	1.037	1.036	1.032	1.032	1.302	1.028	1.037	1.036	1.032	1.032	1.625	1.028	1.037	1.036	1.032	1.032	1.187	1.028
ϕ_Y	0.970	0.841	0.910	0.931	0.978	0.965	0.970	0.844	0.911	0.932	0.979	0.965	0.970	0.847	0.913	0.933	0.979	0.966	0.970	0.856	0.902	0.935	0.978	0.965
A	5.606	9.010	7.421	6.906	4.768	5.786	5.602	8.954	7.398	6.894	4.766	5.780	5.598	8.872	7.364	6.877	4.765	5.771	5.598	8.655	7.587	6.842	4.769	5.780
κ	1.038	1.038	1.031	1.014	1.016	1.014	1.038	1.038	1.031	1.014	1.016	1.014	1.038	1.038	1.031	1.014	1.016	1.014	1.038	1.038	1.031	1.014	1.016	1.014
Calibrated result																								
ε^*	0.017	0.024	0.023	0.028	0.012	0.008	0.017	0.024	0.023	0.028	0.012	0.008	0.017	0.024	0.023	0.028	0.012	0.008	0.017	0.024	0.023	0.028	0.012	0.008
μ^*	0.039	0.056	0.055	0.068	0.028	0.020	0.039	0.056	0.055	0.068	0.028	0.020	0.039	0.056	0.055	0.068	0.028	0.020	0.039	0.056	0.055	0.068	0.028	0.020
q_0^*	0.748	0.806	0.754	0.727	0.649	0.684	0.748	0.806	0.754	0.727	0.649	0.684	0.748	0.806	0.754	0.727	0.649	0.684	0.748	0.806	0.754	0.727	0.649	0.684
q_1^*	0.758	0.825	0.770	0.746	0.655	0.689	0.758	0.825	0.770	0.746	0.655	0.689	0.758	0.825	0.770	0.746	0.655	0.689	0.758	0.825	0.770	0.746	0.655	0.689
m_0^*	0.655	0.813	0.735	0.962	0.499	0.420	0.656	0.814	0.736	0.962	0.500	0.421	0.657	0.816	0.737	0.962	0.500	0.421	0.657	0.820	0.731	0.963	0.499	0.421
m_1^*	0.869	1.247	0.992	1.028	0.615	0.589	0.870	1.249	0.993	1.028	0.616	0.589	0.871	1.251	0.994	1.029	0.616	0.590	0.871	1.258	0.987	1.029	0.615	0.589
p^*	0.259	0.140	0.182	0.201	0.682	0.440	0.260	0.140	0.183	0.202	0.685	0.442	0.262	0.141	0.185	0.204	0.690	0.445	0.262	0.145	0.176	0.207	0.679	0.442
s^*	2.952	2.842	2.916	3.229	2.266	1.733	2.952	2.842	2.916	3.229	2.266	1.733	2.952	2.842	2.916	3.229	2.266	1.733	2.952	2.842	2.916	3.229	2.266	1.733
h_0^*	11.936	152.158	62.296	36.459	0.164	24.344	11.788	149.453	61.354	35.979	0.128	24.056	11.568	145.480	59.963	35.269	0.075	23.628	11.568	134.876	69.057	33.792	0.197	24.056
h_1^*	15.827	233.424	84.065	38.975	0.202	34.092	15.631	229.275	82.793	38.462	0.158	33.688	15.339	223.180	80.917	37.703	0.092	33.089	15.339	206.913	93.188	36.124	0.242	33.688
x_0^*	16.463	22.098	15.444	16.800	5.651	10.093	16.463	22.098	15.444	16.800	5.651	10.093	16.463	22.098	15.444	16.800	5.651	10.093	16.463	22.098	15.444	16.800	5.651	10.093
x_1^*	21.830	33.901	20.841	17.960	6.963	14.134	21.830	33.901	20.841	17.960	6.963	14.134	21.830	33.901	20.841	17.960	6.963	14.134	21.830	33.901	20.841	17.960	6.963	14.134
w^*	5.147	5.959	5.767	5.765	4.408	5.112	5.147	5.959	5.767	5.765	4.408	5.112	5.147	5.959	5.767	5.765	4.408	5.112	5.147	5.959	5.767	5.765	4.408	5.112
k^*	0.161	0.215	0.168	0.197	0.068	0.076	0.160	0.214	0.168	0.197	0.068	0.076	0.160	0.214	0.167	0.197	0.068	0.075	0.160	0.213	0.168	0.197	0.068	0.076
π^*	0.843	6.990	4.173	2.355	0.229	2.484	0.834	6.868	4.112	2.327	0.223	2.456	0.820	6.688	4.022	2.284	0.214	2.413	0.820	6.209	4.609	2.196	0.235	2.456
y^*	5.305	7.067	6.327	6.183	4.503	5.292	5.304	7.047	6.320	6.179	4.503	5.291	5.303	7.018	6.309	6.173	4.502	5.288	5.303	6.942	6.382	6.160	4.503	5.291

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. All common parameters, except for ζ, share identical values as those listed in Table 1.

Table A15: Robustness test for ζ - impacts of subsidy to domestic doctoral students

	ζ=15% (baseline)						ζ=16%						ζ=17.5%						varying ζ					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
ζ	0.150	0.150	0.150	0.150	0.150	0.150	0.160	0.160	0.160	0.160	0.160	0.160	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.217	0.082	0.207	0.141	0.160
Wage of domestic doctoral student																								
s^*	2.469	2.326	2.453	2.898	1.802	1.034	2.469	2.327	2.453	2.901	1.800	1.034	2.472	2.330	2.453	2.901	1.794	1.034	2.472	2.334	2.450	2.900	1.803	1.034
$\bar{s}$	0.490	0.522	0.472	0.340	0.464	0.705	0.490	0.520	0.471	0.341	0.467	0.705	0.490	0.519	0.470	0.340	0.471	0.704	0.490	0.514	0.476	0.339	0.461	0.705
Percentage change relative to the corresponding benchmark economy																								
ε^*	-21.68%	-22.13%	-19.44%	-13.86%	-6.06%	-90.48%	-22.28%	-22.34%	-19.66%	-13.51%	-5.20%	-91.07%	-21.68%	-22.55%	-20.09%	-13.86%	-3.90%	-92.85%	-21.68%	-23.62%	-17.91%	-14.39%	-7.36%	-91.07%
$\mu^* - \varepsilon^*$	16.57%	21.19%	18.13%	10.64%	3.44%	64.45%	16.57%	21.19%	18.13%	10.51%	2.81%	64.45%	16.35%	21.04%	18.13%	10.51%	1.88%	64.45%	16.35%	20.88%	18.29%	10.51%	4.06%	64.45%
μ^*	0.51%	3.03%	2.38%	0.37%	-0.54%	-0.50%	0.25%	2.94%	2.29%	0.44%	-0.54%	-0.74%	0.38%	2.76%	2.11%	0.29%	-0.54%	-1.49%	0.38%	2.23%	3.11%	0.07%	-0.73%	-0.74%
q_0^*	0.13%	0.15%	0.12%	0.14%	0.03%	0.27%	0.14%	0.15%	0.13%	0.13%	0.02%	0.27%	0.13%	0.16%	0.14%	0.14%	0.02%	0.28%	0.13%	0.18%	0.09%	0.15%	0.03%	0.27%
q_1^*	0.14%	0.22%	0.17%	0.15%	0.02%	0.26%	0.14%	0.22%	0.17%	0.14%	0.02%	0.27%	0.14%	0.22%	0.18%	0.15%	0.01%	0.27%	0.14%	0.23%	0.16%	0.15%	0.03%	0.27%
m_0^*	19.75%	26.92%	21.49%	11.08%	3.95%	87.24%	19.81%	26.94%	21.51%	10.95%	3.24%	87.25%	19.50%	26.79%	21.55%	10.95%	2.18%	87.47%	19.50%	26.74%	21.53%	10.96%	4.68%	87.25%
m_1^*	19.75%	26.92%	21.49%	11.08%	3.94%	87.24%	19.81%	26.94%	21.51%	10.95%	3.24%	87.25%	19.50%	26.79%	21.55%	10.95%	2.18%	87.47%	19.50%	26.74%	21.53%	10.96%	4.68%	87.25%
p^*	-0.56%	-2.28%	-1.32%	-0.22%	0.37%	-4.67%	-0.42%	-2.32%	-1.34%	-0.36%	0.37%	-4.86%	-0.71%	-2.34%	-1.32%	-0.33%	0.39%	-4.86%	-0.71%	-2.37%	-1.38%	-0.35%	0.54%	-4.86%
$s^* + \bar{s}$	0.24%	0.22%	0.28%	0.27%	0.03%	0.35%	0.22%	0.17%	0.26%	0.37%	0.03%	0.34%	0.36%	0.23%	0.22%	0.35%	-0.05%	0.31%	0.36%	0.18%	0.31%	0.31%	-0.04%	0.34%
h_0^*	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%	0.01%	3.67%	2.00%	-0.45%	-18.03%	11.02%	-0.10%	3.69%	2.03%	-0.45%	-19.13%	11.13%	-0.10%	3.81%	1.89%	-0.46%	-16.72%	11.02%
h_1^*	-0.01%	3.64%	1.98%	-0.43%	-17.35%	11.03%	0.01%	3.67%	2.00%	-0.45%	-18.03%	11.02%	-0.10%	3.69%	2.03%	-0.45%	-19.13%	11.13%	-0.10%	3.81%	1.89%	-0.46%	-16.72%	11.02%
x_0^*	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%	2.58%	0.36%	0.66%	0.83%	2.90%	1.87%	2.59%	0.37%	0.68%	0.85%	2.04%	1.91%	2.59%	0.40%	0.59%	0.88%	3.97%	1.87%
x_1^*	2.55%	0.36%	0.65%	0.83%	3.44%	1.84%	2.58%	0.36%	0.66%	0.83%	2.90%	1.87%	2.59%	0.37%	0.68%	0.85%	2.04%	1.91%	2.59%	0.40%	0.59%	0.88%	3.97%	1.87%
w^*	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%	-0.01%	-0.66%	-0.19%	0.03%	0.05%	-0.38%	-0.00%	-0.64%	-0.19%	0.03%	0.04%	-0.37%	-0.00%	-0.62%	-0.20%	0.03%	0.07%	-0.38%
k^*	-0.22%	-4.21%	-2.17%	0.38%	2.92%	-10.64%	-0.24%	-4.23%	-2.18%	0.39%	2.47%	-10.63%	-0.16%	-4.23%	-2.21%	0.39%	1.73%	-10.71%	-0.16%	-4.32%	-2.10%	0.40%	3.35%	-10.63%
π^*	-2.47%	3.28%	1.33%	-1.24%	-20.07%	9.04%	-2.48%	3.30%	1.33%	-1.26%	-20.32%	9.00%	-2.59%	3.31%	1.35%	-1.28%	-20.73%	9.07%	-2.59%	3.40%	1.30%	-1.32%	-19.87%	9.00%
y^*	-0.01%	-0.67%	-0.19%	0.03%	0.06%	-0.38%	-0.01%	-0.67%	-0.19%	0.03%	0.05%	-0.38%	-0.00%	-0.65%	-0.19%	0.03%	0.04%	-0.38%	-0.00%	-0.62%	-0.20%	0.03%	0.07%	-0.38%
Average lifetime utilities																								
U	-0.04%	-0.40%	-0.14%	-0.02%	0.01%	-0.26%	-0.04%	-0.40%	-0.14%	-0.02%	0.00%	-0.26%	-0.03%	-0.39%	-0.14%	-0.02%	-0.01%	-0.26%	-0.03%	-0.38%	-0.15%	-0.02%	0.01%	-0.26%
U_I	-0.05%	-0.40%	-0.14%	-0.01%	-0.02%	-0.26%	-0.03%	-0.41%	-0.14%	-0.04%	-0.00%	-0.31%	-0.08%	-0.40%	-0.13%	-0.03%	0.02%	-0.29%	-0.08%	-0.39%	-0.17%	-0.03%	0.01%	-0.31%
U_D	-0.03%	-0.35%	-0.10%	0.01%	-0.01%	-0.18%	-0.02%	-0.36%	-0.11%	0.01%	-0.00%	-0.23%	-0.02%	-0.35%	-0.11%	0.01%	-0.00%	-0.22%	-0.02%	-0.34%	-0.12%	-0.00%	-0.00%	-0.23%
U_W	-0.03%	-0.40%	-0.14%	-0.01%	0.01%	-0.26%	-0.03%	-0.40%	-0.14%	-0.01%	0.00%	-0.26%	-0.03%	-0.39%	-0.14%	-0.01%	-0.01%	-0.26%	-0.03%	-0.37%	-0.14%	-0.01%	0.01%	-0.26%

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. All experiments are conducted in the scenario of $\tau = 0.05\%$.

Table A16: Robustness test for ζ - impacts of subsidy to professors' research

	ζ=15% (baseline)						ζ=16%						ζ=17.5%						varying ζ					
	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC	AGG	ENG	SCI	MED	HUM	SOC
ζ	0.150	0.150	0.150	0.150	0.150	0.150	0.160	0.160	0.160	0.160	0.160	0.160	0.175	0.175	0.175	0.175	0.175	0.175	0.175	0.217	0.082	0.207	0.141	0.160
Subsidy to professor																								
$\bar{\rho}_h h_0^*$	0.372	0.517	0.410	0.362	0.231	0.487	0.372	0.516	0.410	0.362	0.231	0.487	0.373	0.515	0.410	0.361	0.230	0.487	0.373	0.511	0.412	0.360	0.231	0.487
$\bar{\rho}_h h_1^*$	0.493	0.793	0.553	0.387	0.285	0.681	0.494	0.792	0.553	0.387	0.284	0.682	0.494	0.790	0.553	0.386	0.284	0.682	0.494	0.785	0.556	0.385	0.285	0.682
Percentage change relative to the corresponding benchmark economy																								
ε^*	4.22%	0.21%	0.66%	1.05%	39.41%	3.55%	4.22%	0.21%	0.66%	1.58%	41.57%	3.55%	3.91%	0.21%	0.66%	1.58%	43.74%	3.55%	3.91%	0.85%	0.66%	1.58%	38.98%	3.55%
$\mu^* - \varepsilon^*$	-2.83%	-0.31%	-0.63%	-0.89%	-23.44%	-2.13%	-2.83%	-0.31%	-0.63%	-1.01%	-24.69%	-2.13%	-2.83%	-0.31%	-0.63%	-1.01%	-26.25%	-2.13%	-2.83%	-0.46%	-0.63%	-1.01%	-22.82%	-2.13%
μ^*	0.13%	-0.09%	-0.09%	-0.07%	2.90%	0.25%	0.13%	-0.09%	-0.09%	0.07%	3.09%	0.25%	0.00%	-0.09%	-0.09%	0.07%	3.09%	0.25%	0.00%	0.09%	-0.09%	0.07%	3.09%	0.25%
q_0^*	-0.03%	-0.00%	-0.00%	-0.01%	-0.18%	-0.01%	-0.03%	-0.00%	-0.00%	-0.02%	-0.19%	-0.01%	-0.02%	-0.00%	-0.00%	-0.02%	-0.19%	-0.01%	-0.02%	-0.01%	-0.00%	-0.02%	-0.18%	-0.01%
q_1^*	-0.03%	-0.00%	-0.01%	-0.01%	-0.15%	-0.01%	-0.03%	-0.00%	-0.01%	-0.02%	-0.16%	-0.01%	-0.02%	-0.00%	-0.01%	-0.02%	-0.17%	-0.01%	-0.02%	-0.01%	-0.01%	-0.02%	-0.15%	-0.01%
m_0^*	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%	-3.31%	-0.36%	-0.73%	-1.06%	-27.11%	-2.59%	-3.29%	-0.36%	-0.73%	-1.05%	-28.75%	-2.59%	-3.29%	-0.60%	-0.73%	-1.05%	-25.13%	-2.59%
m_1^*	-3.31%	-0.36%	-0.73%	-0.92%	-25.78%	-2.59%	-3.31%	-0.36%	-0.73%	-1.06%	-27.11%	-2.59%	-3.29%	-0.36%	-0.73%	-1.05%	-28.75%	-2.59%	-3.29%	-0.60%	-0.73%	-1.05%	-25.13%	-2.59%
p^*	-0.11%	0.08%	0.06%	0.06%	-1.70%	-0.05%	-0.09%	0.08%	0.06%	-0.08%	-1.63%	-0.03%	0.06%	0.08%	0.07%	-0.07%	-1.26%	-0.01%	0.06%	-0.08%	0.03%	-0.04%	-2.04%	-0.03%
s^*	0.10%	-0.02%	-0.01%	-0.04%	-1.28%	0.18%	0.07%	-0.03%	-0.02%	0.07%	-1.28%	0.16%	0.02%	-0.04%	-0.03%	0.05%	-1.80%	0.12%	0.02%	0.10%	0.05%	0.01%	-0.94%	0.16%
$(1+\bar{\rho}_h)h_0^*$	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%	-0.05%	-0.04%	-0.07%	0.03%	151.98%	-0.39%	-0.02%	-0.04%	-0.07%	0.03%	278.36%	-0.38%	-0.02%	-0.12%	-0.07%	0.03%	91.97%	-0.39%
$(1+\bar{\rho}_h)h_1^*$	-0.06%	-0.04%	-0.07%	0.04%	114.23%	-0.39%	-0.05%	-0.04%	-0.07%	0.03%	151.98%	-0.39%	-0.02%	-0.04%	-0.07%	0.03%	278.36%	-0.38%	-0.02%	-0.12%	-0.07%	0.03%	91.97%	-0.39%
x_0^*	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%	-0.47%	-0.01%	-0.02%	-0.08%	-24.72%	-0.08%	-0.48%	-0.01%	-0.03%	-0.09%	-27.24%	-0.08%	-0.48%	-0.01%	-0.02%	-0.09%	-21.85%	-0.08%
x_1^*	-0.47%	-0.01%	-0.02%	-0.07%	-22.92%	-0.08%	-0.47%	-0.01%	-0.02%	-0.08%	-24.72%	-0.08%	-0.48%	-0.01%	-0.03%	-0.09%	-27.24%	-0.08%	-0.48%	-0.01%	-0.02%	-0.09%	-21.85%	-0.08%
w^*	0.00%	0.01%	0.01%	-0.00%	-0.47%	0.01%	0.00%	0.01%	0.01%	-0.00%	-0.52%	0.01%	-0.00%	0.01%	0.01%	-0.00%	-0.58%	0.01%	-0.00%	0.02%	0.01%	-0.00%	-0.45%	0.01%
k^*	0.03%	0.05%	0.07%	-0.04%	-20.43%	0.40%	0.03%	0.05%	0.07%	-0.03%	-22.16%	0.39%	-0.00%	0.05%	0.07%	-0.04%	-24.62%	0.39%	-0.00%	0.13%	0.07%	-0.04%	-19.38%	0.39%
π^*	-2.73%	-0.38%	-0.70%	-0.88%	-4.91%	-2.31%	-2.76%	-0.38%	-0.71%	-0.90%	-4.38%	-2.34%	-2.78%	-0.39%	-0.72%	-0.91%	-3.82%	-2.37%	-2.78%	-0.49%	-0.64%	-0.94%	-5.06%	-2.34%
y^*	0.00%	0.01%	0.01%	-0.00%	-0.48%	0.01%	0.00%	0.01%	0.01%	-0.00%	-0.52%	0.01%	-0.00%	0.01%	0.01%	-0.00%	-0.59%	0.01%	-0.00%	0.02%	0.01%	-0.00%	-0.45%	0.01%
Average lifetime utilities																								
U	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%	-0.03%	-0.02%	-0.02%	-0.03%	-0.37%	-0.02%	-0.03%	-0.02%	-0.02%	-0.03%	-0.42%	-0.02%	-0.03%	-0.02%	-0.02%	-0.03%	-0.33%	-0.02%
U_I	-0.05%	-0.00%	-0.01%	-0.01%	0.02%	-0.07%	-0.05%	-0.00%	-0.01%	-0.03%	0.04%	-0.07%	-0.02%	-0.00%	-0.01%	-0.03%	0.13%	-0.06%	-0.02%	-0.04%	-0.02%	-0.03%	-0.06%	-0.07%
U_D	-0.03%	-0.02%	-0.02%	-0.03%	-0.37%	-0.04%	-0.03%	-0.02%	-0.03%	-0.03%	-0.36%	-0.04%	-0.02%	-0.02%	-0.03%	-0.03%	-0.41%	-0.04%	-0.02%	-0.02%	-0.02%	-0.03%	-0.36%	-0.04%
U_W	-0.03%	-0.02%	-0.02%	-0.03%	-0.35%	-0.02%	-0.03%	-0.02%	-0.02%	-0.03%	-0.38%	-0.02%	-0.03%	-0.02%	-0.03%	-0.03%	-0.43%	-0.02%	-0.03%	-0.02%	-0.02%	-0.03%	-0.34%	-0.02%

Note: Columns of AGG, ENG, SCI, MED, HUM, and SOC represent the aggregate, engineering, science, medical sciences, humanities, and social sciences, respectively. All experiments are conducted in the scenario of $\tau = 0.05\%$.

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