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ABSTRACT

Skilled Immigration and Innovation: Evidence from Enrollment Fluctuations in U.S. Doctoral Programs

We study the contribution of foreign science and engineering talent to the creation of new knowledge in the U.S. economy using panel data on 2300 science and engineering (S&E) departments at 100 large American universities from 1973 to 1998. We use macroeconomic shocks and policy changes in source countries that differentially affect enrollments across fields and universities to isolate exogenous variation in the supply of students at specific departments. Both foreign and domestic graduate students are central inputs into knowledge creation, and the marginal foreign student contributes more to the production of scientific publications and citations. A 10% decrease in the foreign share of doctoral students lowers S&E research output at U.S. universities by 5-6%. A theoretical model of university admissions and scholarships helps us infer the productivity effects of student quality, and econometric results indicate that any visa restrictions limiting entry of high-quality foreign students is most costly for U.S. innovation. Increased diversity appears to be the primary mechanism by which foreign students improve research outcomes. The impact of more restrictive immigration policies depends on how they affect the quality margin and diversity of incoming foreigners.

JEL Classification: 015, 031 and P33
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1. Introduction

U.S. immigration policy arouses strong passions among politicians and in the popular media. Among academic economists the debate has centered on the effects of immigration on native wages (Card 1990, Altonji and Card 1991, Borjas 1994, 2003, Borjas, Freeman and Katz 1997, Ottaviano and Peri 2005). This issue extends to skilled labor. For example, Borjas (2005) points out that doctoral student immigration has a significant adverse effect on wages of competing high-skilled U.S. workers. On the other hand, the United States has a global comparative advantage in science and innovation and in creating technology-driven new products and markets. The U.S. trade deficit is smallest in high-tech industries (Freeman 2005). Large imports of foreign doctoral students in science and engineering may be an important reason the United States has sustained its primary position as developer of new scientific knowledge, even with deficiencies in math and science training among American secondary school students.[1]

This paper explores whether and how foreign graduate students contribute to developing knowledge in science and engineering (S&E) at U.S. universities. We exploit fluctuations in the supply of foreign students stemming from macroeconomic and policy shocks in source countries to examine the effects of doctoral students in specific disciplines and universities on scientific publications and citations produced in those labs. Since the advent of tighter restrictions on the issuance of U.S. education visas after September 11, 2001 it has been increasingly argued in the media[2] and in prominent

[1] OECD (2006) reports that students aged 15 in the United States ranked 24th in mathematics and 19th in science among 29 countries. Freeman (2009) notes that "the U.S. has come to rely extensively on the immigration of highly educated persons to maintain a lead position in science and technology."
[2] A letter to this effect was published by a broad coalition of U.S. professors and administrators as "Academics Warn of Crisis over Visa Curbs", *Financial Times* May 16, 2004. See also "Visas and Science: Short-Sighted," *The Economist*, May 8, 2004.

science journals[3] that the ability of American universities to undertake scientific research is dependent on technically trained international graduate students. In turn, restrictive visa policies could cause "…a crisis in research and scholarship" and harm the nation's innovative capacity.[4]

There are clear indications at a descriptive level that foreign students are important contributors to knowledge creation at U.S. universities. Foreign enrollments have increased in absolute and relative (to American enrollments) terms since the 1970s. Foreign students are disproportionately more likely to earn graduate degrees in S&E, and now outnumber Americans in U.S. engineering departments (Council of Graduate Schools). Black and Stephan's (2008) survey of articles published in *Science* finds that 86.5% of papers have a student or post-doc author, and 60% of those authors are foreign-born. The authors conclude that international graduate students and postdocs are important in staffing labs and playing lead roles in university research. Regarding subsequent innovation, studies document that patent applications in the United States are correlated with foreign student enrollments at the aggregate national level (Chellaraj, et al 2008) and with post-doctoral enrollments at the university level (Gurmu, et al 2009). These provocative correlations between enrollments and patent productivity could be driven by omitted variables (e.g. if student applications surge when departmental faculty quality improves), and deserve further scrutiny.

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[3] "Security Restrictions Lead Foreign Students to Snub US Universities," *Nature,* September 15, 2004. See also "The Knowledge Economy: Is the United States Losing Its Competitive Edge?" The Report of the Task Force on the Future of American Innovation, 16 Feb 2005.

[4] Partly because of tighter limits on student visas since 2001, the number of foreign graduate students in the United States fell by eight percent in 2002 and by a further ten percent in 2003, reversing a 15-year trend of rapid growth. Computer science and other S&E disciplines experienced the largest relative declines, as the U.S. Department of Homeland Security instituted the lengthy *Visa Mantis* security clearance program. A key concern is whether these trends presage a diminution in U.S. leadership in science and innovation.

In this paper we analyze detailed information on individual students to assess the impacts on research outcomes. We assemble a database of student enrollment counts by nationality for 2300 U.S. science and engineering departments for 1973-2004 by aggregating individual records on each doctoral student maintained by the *National Science Foundation*. We combine these records with publications in scientific journals from each of those departments, which are compiled from publication and citation searches on the Institute for Scientific Information's *Web of Science*.

To isolate the causal impacts of doctoral students, we devise an instrumental-variables strategy using the idea that macroeconomic shocks and policy changes in source countries lead to plausibly exogenous variation in the supply of foreign students. For example, macroeconomic crises in East Asia or decisions by Chinese authorities to permit their students to enter graduate programs abroad tended exogenously to alter student supplies in the United States. Moreover, these shocks would have differentially larger impacts on research outputs in fields of study that are traditionally more popular among Asians and on universities that have traditionally recruited more students from that region. Even if some relevant events in America happen to coincide with those shocks (e.g. the 1980 Bayh-Dole Act and the roughly simultaneous lifting of study-abroad restrictions in China), the event is unlikely to affect publishing along the same patterns of universities and disciplines as the foreign shocks. Our specifications add fixed effects for all 2300 departments, and university-specific and field-specific trends, so that empirical inference is based only on changes in publishing in an academic department following fluctuations in student enrollments in that department.

We find that foreign doctoral students significantly and positively influence publications and citations produced by U.S. academic departments. Each additional foreign student leads to 0.5 to 1.7 extra S&E journal articles, which translates into an elasticity of 0.2 to 0.6. The marginal effect of foreign students significantly exceeds that of Americans, which is consistent with an optimizing department that finds it less costly to educate Americans or one that extracts greater teaching value from Americans.

We further show that the type (quality) of entering foreign doctoral students matters greatly for research productivity. Unfortunately, we do not have direct measures of student quality. However, we develop a theoretical model of admissions decisions in which universities trade off student quality and tuition income and show that comparing across different sets of source-country shocks that differentially affect student ability-to-pay allows us to distinguish empirically the productivity effects of higher-quality and lower-quality students. Empirically, Americans are comparable to, or even exceed in productivity, foreigners in the lower-quality category comprised of students pay for graduate education. And international scholarship students are most productive at elite universities. These results suggest that from the perspective of U.S. science education and innovation policy, visa restrictions for foreign students should not be applied uniformly; they ought to account for incoming student-quality differences.

While an increase in foreign-student share changes the mix of nationalities, it also increases diversity in the average U.S. S&E department (where 69 percent of doctoral students are American). We create a student region-of-origin diversity index (instrumented by the mix of policy and macro shocks in various source regions) to unpack the mechanism behind these positive foreign-student effects. We find that the diversity mechanism dominates any nationality effects. Departments that enroll student cohorts from a wider variety of global regions are considerably more productive: the elasticity of publications and citations with respect to diversity is about unity.

The increasing dominance of laboratory teams and co-authoring in the production of scientific knowledge is well documented (Jones, Uzzi and Wuchty 2008) and our results show that the international composition of teams matters. Diversity of the student body can generate positive spillovers from the exchange and mixing of ideas, training and methods if students from different regions bring complementary and heterogenous skills (Ottaviano and Peri 2006, Alesina and Ferrara 2005, Berliant and Fujita 2004, Fujita and Weber 2005, and Niebuhr 2006). Or it could facilitate the growing trend towards cross-country research collaborations (Adams, et al 2005). Our findings supplement the theoretical and empirical literatures on teamwork and peer effects (Kremer 1993, Becker and Murphy 1992, Ichniowski, et al 1997, Mas and Moretti 2009, and Waldinger 2009).

Our analysis thus documents a key benefit of high-skilled immigration in the United States, which relies on innovation for growth. The mainstream media is inundated with quotes from universities and employers on the economic dangers of visa restrictions.[5] It is therefore important to estimate precisely the causal returns to foreign-student presence so that immigration policy-makers can value the tradeoff between such knowledge gains and the costs of tuition subsidies and congestion claimed by Borjas (2002, 2004). Our results add to the literature documenting other benefits of immigration (Cortes 2009, Mishra 2005).

[5] See *New York Times* March 3, 2009 on researchers and academic conferences moving abroad, *Wall Street Journal* March 11, 2009 arguing that productive foreign-born workers create more jobs, and *New York Times* April 12, 2009 on immigration laws making it more difficult for Google to recruit workers.

The paper proceeds as follows. We outline modeling frameworks in section 2, including a tuition income model in 2c to motivate empirical analysis of heterogenous student quality. We present the IV-based empirical approach in section 3, data sources in section 4, and discuss results in section 5. We make concluding remarks in section 6.

2. Modeling Framework

We estimate a knowledge production function. The extensive literature on the determinants of university patenting (Thursby and Thursby 2002, Thursby and Kemp 2002, Jaffe and Trachtenberg 2002, Mowery, et al 2004 and Azoulay, et al 2005) is thus closely related. Regarding the research productivity of foreign students, papers relating patent applications and grants to students and immigrants at the national level (Chellaraj, et al 2008), state level (Hunt and Gauthier-Loiselle 2008), and university level (Gurmu, et al 2009) are closely related.

2a. Insights from Neoclassical Production Function Analysis

The simplest theory by which to interpret our statistical results is a neoclassical production function for an academic department or lab with domestic and foreign graduate students as inputs.[6] A rational resource allocator wishing to maximize a single output with a budget constraint would choose inputs such that the marginal product per dollar spent on each were the same (Pritchett and Filmer 1997). In our setting, research departments would admit domestic and international graduate students to equate the contribution of each type, scaled by some measure of department-level cost of educating them. Such costs could include stipends and the opportunity costs of faculty time.

Domestic graduate students likely are cheaper because of lower tuition costs for state residents at public universities and higher training costs for foreign students due to language difficulties. Further, there is likely to be more uncertainty about student ability for applicants from more remote foreign areas. Accordingly, we should observe higher domestic enrollments and lower marginal products.

University departments generate multiple outputs (research and undergraduate teaching), so they would admit graduate students until the difference in per-dollar marginal products in producing publications equals the difference in per-dollar marginal products in teaching. If, for example, domestic students offer greater productivity as teaching assistants than foreign students, we would observe a greater marginal contribution to producing publications from international doctoral students in equilibrium. In this model all marginal products should be positive. And enrollment shocks should not have a substantial impact on the production of publications because departments would be able to substitute across inputs.

2b.Outline of a Model of Knowledge Creation with Heterogenous Inputs

This approach misses some important details of the reality of what happens in academic research, since it is inaccurate to think of universities as operating with a fixed budget constraint and highly divisible homogeneous inputs. In this section we outline a more suitable modeling framework to motivate our identification strategy based on student-supply shocks in the basic publication and citation regressions. We then solve a simpler version of the model to motivate how different types of macroeconomic shocks

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[6] Hanushek (1979) is the seminal reference. See also Johnson (1978) and de Groot, et al (1991) for examples. These models assume either one output (e.g., test scores) or multiple outputs (e.g., graduate diplomas and research) produced using a variety of inputs, such as faculty size and research funding.

can help us separately identify the effects of scholarship (i.e., higher-quality) students versus paying students, even when we do not have direct measures of student quality.

Suppose that a department *d* produces knowledge using as inputs "professors" *P* (i.e., an index of faculty, grant funding and the like) and quality-weighted students from the United States, *u* and two foreign regions, *g* and *h*:

$$K_{dt} = K_d(P_{dt}, \sum_{u=1}^{U} q_{dt}^{u} + \sum_{g=1}^{G} q_{dt}^{g} + \sum_{h=1}^{H} q_{dt}^{h}) \qquad (1)$$

The creation of knowledge rises in both faculty quality and the quality-weighted number of graduate students. The production function reflects the fact that students are not the only input and students are themselves heterogeneous in their ability to contribute to knowledge creation. Departments limit enrollments due to resource constraints and for quality control. For simplicity, assume that a department's capacity to enroll graduate students at any time is strictly constrained:

$$U_{dt} + G_{dt} + H_{dt} = \overline{S_{dt}} \qquad (2)$$

Foreign students are costly to admit but this cost declines as departments gain experience with students from different regions:

$$C_{dt} = c_{dt}^{g}(G_{d,t-1}) \cdot G_t + c_{dt}^{h}(H_{d,t-1}) \cdot H_t \text{, where } c_g, c_h \geq 0 \text{ and } c_g^{'}, c_h^{'} \leq 0 \qquad (3)$$

Normalizing the cost of training an American to zero, we permit these cost functions to vary between regions. As departments gain more experience with students from a particular region (indexed here by lagged enrollments), these costs diminish.

Economic conditions can affect both the supply and quality of students available, because their incentives and ability to apply depend on labor market conditions (e.g., wage available in alternative employment), macroeconomic factors (e.g., exchange rate changes that affect ability to incur cost of travel and emigration limits or visa restrictions). Thus, a student from region *G* applies to department *d* at time *t* if $P_{dt} + \varepsilon_{dt}^{g} \geq w_t^G$, or if the benefits she gets from studying at department *d* (determined by department quality *P* plus her idiosyncratic preference to study there) exceed the "outside option" *w* (e.g., the wage a college graduate would get in her region).

Departments admit students with the highest value added (*K* – *C*), taking into account student quality and region-specific costs. Experience with regions will matter in these admissions decisions over time, as the cost of admitting students from a region decreases as universities invest in learning about students from that region (or conversely, the region's students learn about the university). Since students prefer to attend higher-quality universities and universities prefer better students, the matching process assigning applicants to departments will likely be assortative.

This framework clarifies endogeneity problems arising in regression models that relate enrollments to departmental output and the nature of the resulting bias. It also suggests possible solutions. Suppose that in a particular year a specific department experiences a positive shock to *P*. This positive shock would increase a department's knowledge production independent of any changes to its enrollments of students. The shock would also attract both more Americans and more foreigners to apply. In a regression of publications on the foreign-student share, the direction of the resulting bias would depend on which type of students ultimately enroll as a result of this shock. If departments show a preference for Americans over foreigners in the admissions decision (e.g., because $c_g, c_h \geq 0$), enrollments will shift in favor of the former and the coefficient on foreign student enrollment in the publications regression would be biased in the negative direction.

The model also suggests that shocks to the outside option (i.e., w^G, w^H) may be used as instruments to identify exogenous fluctuations in the numbers of foreigners enrolling in graduate programs in the United States. Moreover, shocks in particular regions may have differential effects on enrollments across different departments by virtue of the fact that a department's history with students from a region can matter in the admissions decision ($c_g^{'}(G_{d,t-1}) \leq 0$). Interaction terms between region-specific shocks and department-region enrollment histories may yield powerful instruments that identify shock-induced, department-specific fluctuations. We will take advantage of these insights in developing an estimation strategy in section 3.

2c. A Simple Model with Student Quality, Tuition and Scholarships

A key visa policy question of interest is whether immigration restrictions should account for the quality of incoming students. Given the costs associated with admitting foreign students (Borjas 2002, 2004, 2005), the optimal policy may be to allow only students above a certain ability threshold who are likely to contribute more to innovation and U.S. competitiveness. U.S. visa policy for foreign students has traditionally paid more attention to financial resources and assets held abroad to infer students' incentives to remain in the United States past graduation, which is curiously viewed as a negative outcome.[7]

We would like to estimate the differential contributions to innovation from high-quality and low-quality foreign students to inform this debate. Unfortunately, there are no direct empirical measures of a student's "quality". Further, even if such measures existed, we would have to account for the endogenous placement of higher-quality students. Given these constraints, we now solve a simplified version of a Ph.D.-admissions model to highlight how student-quality effects can still be estimated under the reasonable premise that: (a) higher-quality students are more likely to receive scholarships, and (b) certain source-country macroeconomic conditions cause differentially larger fluctuations in non-scholarship students.

Suppose universities care about student quality q and tuition income m (per-student). The population of potential students is divided into N^R rich applicants who can afford to pay tuition and N^P poor applicants who are credit-constrained and can only attend with a scholarship. The distribution of student quality in both groups is $f(q)$. With a convex cost function $c(\cdot)$ that reflects the congestion costs of admitting more students, and marginal benefits of quality and tuition to the university denoted as A and B respectively, the university's objective function becomes:

$$\begin{aligned} U &= A(N^R + N^P)\int_{q_s}^{\infty} qf(x)dx + AN^R\int_{q_n}^{q_s} qf(x)dx + BN^R\int_{q_n}^{q_s} mf(x)dx \\ &- c\left[N^P\int_{q_s}^{\infty} f(x)dx + N^R\int_{q_n}^{\infty} f(x)dx\right] \end{aligned} \tag{4}$$

The university maximizes over q_s and q_n, the lower quality bounds for admitted scholarship and non-scholarship students, respectively. The university cannot observe whether students are rich or poor, so it gives scholarships to all students with quality exceeding q_s, although some of those students are rich. For algebraic tractability, we will

[7] Applicants for F-1 student visas must demonstrate that they have enough readily available funds to meet all expenses during a course of study and agree to leave the United States after completing their education (http://www.usastudyguide.com/immigration.htm).

assume that $c(x)=\frac{C}{2}x^2$ (with a constant *C*) and that $f(q)\sim U[0,\bar{q}]$.[8] The first order conditions simplify to:

$$-AN^P q_s + BN^R m + N^P C\left[N^P\frac{\bar{q}-q_s}{\bar{q}} + N^R\frac{\bar{q}-q_n}{\bar{q}}\right]=0 \qquad (5a)$$

$$-Aq_n - Bm + C\left[N^P\frac{\bar{q}-q_s}{\bar{q}} + N^R\frac{\bar{q}-q_n}{\bar{q}}\right]=0 \qquad (5b)$$

We can obtain closed-form solutions to q_s and q_n by solving (5a) and (5b). This shows that $q_s > q_n$, as expected. Taking derivatives with respect to the numbers of rich and poor students:

$$\begin{aligned}
\frac{\partial q_s}{\partial N^P} &= \frac{A^2\bar{q}^2(C(N^P)^2 - BmN^R) - 2ABCmN^R\bar{q}(N^P+N^R) - BC^2mN^R(N^P+N^R)^2}{A(N^P)^2(A\bar{q}+C(N^P+N^R))^2}\\
\frac{\partial q_s}{\partial N^R} &= \frac{A^2CN^P\bar{q}^2 + Bm(A\bar{q}+C(N^P+N^R))^2}{AN^P(A\bar{q}+C(N^P+N^R))^2}\\
\frac{\partial q_n}{\partial N^P} &= \frac{\partial q_n}{\partial N^R} = \frac{AC\bar{q}^2}{(A\bar{q}+C(N^P+N^R))^2}
\end{aligned} \qquad (6)$$

Since total graduate student quality is $Q = N^P\int_{q_s}^{\infty} qf(q)dq + N^R\int_{q_n}^{\infty} qf(q)dq$

$=\frac{1}{2}N^P(\bar{q}-\frac{q_s^2}{\bar{q}})+\frac{1}{2}N^R(\bar{q}-\frac{q_n^2}{\bar{q}})$, the effects of a change in N^R or N^P on *Q* are:

$$\begin{aligned}
\frac{\partial Q}{\partial N^P} &= \frac{1}{2}\bar{q} - \frac{q_s^2}{2\bar{q}} - \frac{N^P}{\bar{q}}q_s\frac{\partial q_s}{\partial N^P} - \frac{N^R}{\bar{q}}q_n\frac{\partial q_n}{\partial N^P}\\
\frac{\partial Q}{\partial N^R} &= \frac{1}{2}\bar{q} - \frac{q_n^2}{2\bar{q}} - \frac{N^P}{\bar{q}}q_s\frac{\partial q_s}{\partial N^R} - \frac{N^R}{\bar{q}}q_n\frac{\partial q_n}{\partial N^R}
\end{aligned} \qquad (7)$$

Plugging the expressions from (6) into (7), we get:

[8] A normal distribution for ability may be more realistic, but the uniform distribution with a large upper-bound $\bar{q}$ is a reasonable approximation to the far right tail of the normal distribution, where applicants to Ph.D. programs are likely to reside.

$$\frac{\partial Q}{\partial N^P} - \frac{\partial Q}{\partial N^R} = \frac{B^2 m^2 (N^P + N^R)^2}{2A^2 (N^P)^2 \overline{q}} \qquad (8)$$

This expression is always positive, so a positive shock to the number of poor applicants increases graduate student quality by more than a positive shock to the number of rich applicants. This is the main insight we will take advantage of in our empirical analysis of the effects of student quality. Specifically, even in the absence of direct measures of quality, we can infer quality effects through this scholarship mechanism if we can identify separate sets of foreign-country shocks that differentially affect the application propensities of rich versus poor students.

Equation (8) further reveals that if B or m is large (i.e., if the value of paying students to the school is high), then a shock to the number of poor students has a much larger effect on total student quality than a comparable shock to rich students. This is because if B or m is large, then the school admits mainly rich students without scholarships, implying that admitted poor students with scholarship are of much higher quality than admitted rich students. This is a testable prediction, since the relative importance of tuition income is likely lower at high-endowment elite universities, which we can identify in the data.

3. Methodology

3a. Basic Specifications

We run the following basic specification to examine the effects of foreign and domestic Ph.D. student enrollments on knowledge produced in specific fields of inquiry within U.S. universities over the period 1973-1998:

$K_{f,u,t} = \alpha_{f,u} + \delta_t + \gamma_u\,(D_u{*}Trend) + \rho_f\,(D_f{*}Trend)\,) + \beta_1 * Total\_Students_{\,f,u,t\text{-}l} + \beta_2 *$
$Foreign\_Share_{\,f,u,t\text{-}l} + \beta_3 * R\&D\_Exp_{\,f,u,MA(t\text{-}l,t\text{-}5)} + \varepsilon_{f,u,t}$ (9)

The variable *K* refers to either publications or citations. The dataset has four identifiers – the students' region of origin (e.g., South Asia), the university *u* at which students are enrolled, the field of inquiry *f* (e.g., industrial engineering), and year *t*. We will refer to the university-field pair as an academic "department". Equation (9) explains variation in scientific publications or citations in a given department and year as a function of total enrollments and the foreign-student share in the previous year, while controlling for fixed effects for every department, linear trends specific to each university and each field, year dummies and, in some specifications, controls for departmental resources (equipment, capital and R&D expenditures, including faculty salaries). The fixed effects control for time-invariant differences in characteristics across departments. The field-specific and university-specific trends capture any linear changes in the norms regarding publishing at a particular university or within a field of inquiry.[9]

After controlling for department fixed effects, time dummies and specific field and university trends, the remaining objects of concern are unobservable characteristics specific to academic departments that vary non-linearly over time and affect both the publications produced by those departments and their student enrollments. For example, if the quality of a department improves, say through greater funding and better faculty recruitment, in a dimension not fully captured by the R&D expenditure controls, it may

[9] The average number of publications per department rose from 25 in the 1970s to 54 in the 1980s, while citations rose from 832 to 1,654. Thus, it seems reasonable to think of the dependent variables as continuous, and we run linear regressions. We have also run negative binomial fixed-effects count-data models of the following form $K_{f,u,t} = e^{X_{f,u,t}\cdot\eta}\cdot\alpha_{fu} + \varepsilon_{f,u,t}$ (where $X_{f,u,t}$ encompasses all variables in (9),

attract greater numbers of foreign students and also have an independent effect on the department's output.[10] Conversely, if an improvement in the quality of a department (and therefore a rise in students' earning potential) attracts high-quality American students away from business, law and other professional degrees and into S&E fields, we may observe drops in foreign-student enrollments when a department's quality improves. Under a preference for Americans in admission, possibly due to language skills, wider ranges of financial-aid options available for natives or greater productivity in teaching, foreign students may get crowded out in a department of limited size once more high-quality American students start applying. This is likely to bias the β_2 coefficient in (9) downward.

3b. Instrumental Variables Estimates

Our solution to this problem is to use an instrumental variable (IV) estimator that takes advantage of plausibly exogenous fluctuations in the supply of foreign students. We instrument for total enrollments and the foreign-student share using economic and policy shocks in the students' countries (or regions) of origin. We choose shocks that influence foreigners' decisions about whether to travel to the United States for graduate study, but that are plausibly uncorrelated with the publications produced at specific academic departments. For example, a currency devaluation in Thailand would reduce Thai students' ability to pay for moving to the United States and their educational start-up costs, in addition to making the cost of a U.S. education more expensive if the student is

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and parameter $\alpha_{f,u}$ is a separate indicator for each field-university pair), and verified that the results are qualitatively very similar.

[10] If the marketability or popularity of a particular field of study among students at a given point in time varies non-linearly, that would be another omitted variable that may bias the impact of foreign students in either direction, depending on how U.S. students respond to such changes.

not on scholarship. This problem can lead to fluctuations in Thai enrollment at U.S. universities but may not affect publishing in specific academic departments through any other channel. To illustrate, Figure 1 plots enrollments of doctoral students from India at U.S. universities against a relevant instrument (Indian GDP growth). The co-movement of enrollment counts and the instrument displayed provides some preliminary indication of its statistical power.

We use fluctuations in source-country policies (e.g., lifting of restrictions on Russian and Chinese students regarding study abroad) and in economic conditions (e.g., income growth and fluctuations in the SDR – local currency exchange rates in East Asia and Latin America) to instrument enrollments. These instruments vary by country and year, while our endogenous variables of interest (foreign students) have richer dimensions of variation, at the level of university, field of study, years of study, and origin. In order to exploit variation across all four dimensions in the data, we use the idea that the vulnerability to a student-supply shock from a particular country will differ by field and university. For example, if Purdue University has traditionally recruited a larger share of Indian students into its graduate programs (and therefore has invested in developing an ability to identify good Indian students), a shock to supply from India is expected to have a differentially larger impact on research at that institution. Similarly, if Indians are more likely to study chemical engineering, then this shock would affect chemical engineering departments more (and perhaps that field at Purdue the most).

Our disaggregated micro-data approach to answering these research questions has the advantage that, in this example, the Indian student shock would manifest itself in disproportionately larger impacts on publishing at Purdue (an institution-specific effect) and at relatively strong chemical engineering departments (a discipline-specific effect). This allows us better to distinguish the effects of student enrollments from coincident changes in economic or policy conditions in the United States that may alter publishing behavior. For example, the general decline in U.S. high-technology industries in the late 1990s may have affected university research output, and it also happened to coincide roughly with the East Asian financial crisis – a student-supply shock that we exploit with our instruments. However, given our IV strategy's reliance on the disproportionate effects of the Asian shock to particular fields and universities, this coincidence would only be a concern if the decline in the high-technology industries just happened to have a greater effect on publishing in the departments that have traditionally relied on East Asian students more. Observing events in the United States that had such specific patterns of influence on academic departments is considerably more unlikely than just finding events that happened to coincide with a foreign-country policy change or economic shock, which increases our confidence in this estimation strategy.

Figures 2-4 demonstrate the empirical relevance of these ideas. Figure 2 shows that there was a tremendous increase in Chinese doctoral students in the United States after the partial (1981) and total (1984) lifting of restrictions on study abroad. Moreover, these enrollments rose with the subsequent growth in Chinese GDP. Figures 3 and 4 further indicate that the University of Texas benefited differentially more from this surge in Chinese enrollments than did the University of California at San Diego and that electrical engineering departments benefited more than biochemistry departments.

We implement these ideas in the statistical analysis by using the following types of interaction terms in our list of instruments:

*[Shock in region r in year t] * [fraction of university u foreign students who are from region r at some initial date t_0] * [fraction of students in field f from region r at t_0]*

We employ aggregated regions rather than specific countries because to instrument at the country level would incorporate so many variables that the problem of having many weak instruments in an over-identified system would be severe. The initial date t_0 is defined to be the start of each decade (1970, 1980, and 1990).

4. Data

4a. Publications and Citations

We create counts of all science and engineering publications associated with the 100 U.S. universities that granted the largest number of foreign doctorates for the period 1973-2001, with data from the Thomson/ISI *Web of Science* database of publications and citations. Using a procedure described more fully in the unpublished data appendix, we sort each university's publication records into 23 S&E fields. Although laboratories and departments are the actual S&E administrative units at U.S. universities, we define "departments" as fields of science and engineering within a university. We extracted 3.2 million individual publication records by writing *Perl* script on the internet-based *Web of Science* database. Using information on the authors' department affiliation(s), the publications' subject categories and the year of publication, each of these records was assigned to one or more of 66,700 (100 x 23 x 29) university-field-year cells.[11] Our final database is a count of publications and total citations in each university-field-year cell. Summary statistics are provided in Table 1.

4b. Enrollment Counts

We create Ph.D. enrollment counts for each data cell (incorporating a university, field, year and country of origin) by aggregating the National Science Foundation *Survey of Earned Doctorates* (SED) micro-database, which contains a record for each individual who received a Ph.D. in the United States between 1959 and the present. Doctoral recipients fill out this survey when they receive the Ph.D. degree, so the yearly enrollment counts we create are based on the graduation date and the date of entry into the doctoral program reported by the students, and reflect only those students who have finished the degree. We infer enrollment counts for the period 1960-1997 only, since there are likely to be many students who entered doctoral programs in 1998 or thereafter who still had not received their degree by 2004, and therefore would not appear in the SED database.

We assign each student to one of 23 fields of study based on the reported three-digit dissertation specialty. The student's assignment by country of origin is based on the reported country of citizenship. Further details are in the unpublished data appendix. We create university-field-year-country enrollment counts for foreign students from the 50 largest countries (those that have supplied at least 930 doctoral students to the United States since 1960) studying in the 100 largest universities (those with at least 2100 doctoral students since 1960), in 23 S&E fields (as defined by Goldberger et al, 1995, also used by Lach and Schankerman, 2008) during the period 1960-1997. There are approximately 700,000 doctoral students in the sample we analyze.

Although we generally exploit country-level variation in the instrumental variables, our second-stage regressions use enrollment counts from all aggregated foreign

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[11] Publications with multiple authors were assigned once to each cell with which an author was affiliated.

students and from aggregated regions of origin rather than the specific country of origin. We define eight regions on the basis of economic, geographic and cultural similarities between countries.

Total doctoral enrollment in the average university-field-year was 42 students, 27 of whom were American. The East Asia/Pacific region was the next largest supplier of students at 4.8, followed by China and then South Asia. Enrollments for U.S. and foreign students are summarized in Table 1.

4c. Instrumental Variables

We describe next the instruments we use for the first-stage prediction of enrollments and the share of foreign students.

(1) Fluctuations in the IMF Special Drawing Right – Foreign Currency Exchange Rate: Movements in, say, the Baht – SDR exchange rate during the Asian financial crisis altered Thais' ability to pay for a U.S. education. Seventy percent of foreign students in the United States are from Asian and Latin American countries, implying that financial-crises-related indicators would predict enrollment fluctuations. Trends in the data are strongly suggestive of their power: student enrollments from Korea, Thailand, Malaysia and Indonesia grew by 41 percent between 1992 and 1997, but dropped by 15.5 percent during the East Asian financial crisis years (1997-1999).

(2) GDP per Capita in Source Countries: In relatively poor countries, this variable captures long-term changes in foreigners' ability to pay for a U.S. education (Figure 1). GDP growth can have the opposite effect in rich countries as it increases employment opportunities in local markets (Sakellaris and Spilimbergo, 2000). To capture such non-monotonic effects, we interact GDP measures with an OECD indicator.

(3) Policy Changes: We create an indicator for country-years where official state policies prohibited students from studying in the United States. As a specific example, this indicator captures the gradual lifting of the ban on study abroad by Chinese S&E students between 1978 and 1984 following the death of Mao Zedong (Orleans 1988). Other countries for which this policy indicator is relevant within our sample period include Russia, Romania, Cuba, Poland, Hungary, Bulgaria, Czechoslovakia and (East) Germany. The unpublished data appendix provides further details.

(4) International Students at non-U.S. Hosts: Using the UNESCO *Statistical Yearbooks* (1963 to present), we create counts of the number of tertiary (university plus post-graduate) foreign students from each source country studying abroad at other (non-U.S.) host countries, such as the United Kingdom, Australia, Singapore, and Canada. The idea is that fluctuations in the number of South Asian students in the United Kingdom and Australia are related to changes in financial conditions and policy changes in South Asia and in those host countries, but uncorrelated with changes in conditions in the United States. To the extent that this instrument explains variation in South Asian students in the United States, the correlation is driven by the commonality between the two variables, which are the economic and policy conditions in South Asia.

5. Results

The empirical results are organized as follows. Table 2a presents the main effect of foreign and domestic S&E doctoral students on publications, and conducts a few specification checks. Table 2b repeats this analysis for citations instead of publications. Table 3 splits the sample and examines knowledge production in early versus late periods, and separately at elite and non-elite universities. Tables 4 and 5 (motivated by the model developed in section 2c) infer student-quality effects by separating supply shocks that send more scholarship versus non-scholarship students to the United States. Finally, Table 6 demonstrates the effects of regional diversity in students within a department on knowledge produced.

The sample period for all regressions is 1973 to 1998, with enrollments lagged one year in order to reflect the lag from research to publication. The 2004 *Survey of Earned Doctorates* provides reliable enrollment counts for the period 1973-1998. All regressions control for a comprehensive set of fixed effects for "departments" (university -field pairs) and years, along with university-specific and field-specific time trends.

5a. Summary Effects of Foreign and Domestic Doctoral Students

Tables 2a and 2b study, respectively, the determinants of the number of scientific publications and the number of citations to those publications in each university-field pair.[12] We examine the relative contributions of domestic and foreign students by constructing the share (proportion) of doctoral students with non-U.S. citizenship, while always controlling for the total Ph.D. enrollment.

The first column in each table (1a and 1b) reports OLS regressions. Larger total Ph.D. enrollment is associated with a larger number of publications and citations. Thus, larger departments produce more knowledge. The negative coefficients on foreign share suggest that the productivity of international students is lower in relative terms. The marginal effects of an additional American student and an additional foreigner depend on both the total-enrollment and foreign-share coefficients, and are computed towards the bottom of each column. Both domestic and international doctoral students positively contribute to the creation of knowledge in absolute terms. Each additional international student in the 'average' department raises publications and citations by about 0.35% (0.15 articles published or 4.4 cites per year), while each additional American increases knowledge output by 0.45% (0.19 publications and 5.4 cites per year). These effects appear small (though not insignificant) relative to the average number of publications (citations) per department per year of 40 (1271).

Regressions 2a (Table 2a) and 2b (Table 2b) use a set of 48 foreign-country economic shocks interacted with lagged regional enrollment fractions (as detailed in section 3c, above) as instruments for both total enrollments and foreign share. This set of instruments, taken together, predicts both total enrollments and the foreign share in the first stage of the 2SLS procedure. The F-statistics for excluded instruments in the two first-stage regressions are 73.09 and 76.97, respectively.

The 2SLS estimates show a positive and significant coefficient on the foreign share of enrollment, which suggests that foreign students are more productive than American students at the margin. Each additional foreign student in a department is associated with just over 0.5 publications and 18 extra citations per year, which translate into an elasticity of about 0.2. Each additional American is associated with 0.33 publications and 4 citations. Foreign contributions are estimated to be larger under 2SLS than under OLS, which suggests that unobserved time-varying determinants of knowledge production are associated with a greater share of Americans enrolling. For

[12] Consistent with the approach in Jaffe and Trajtenberg (2002) we actually use (1 plus counts) as the variable in order to distinguish between observations with no publications (a value of zero) and those with one or more publications that are not cited (a value of one).

example, periods of improved faculty quality and departmental resources induce more Americans to enroll, generating a downward bias in the OLS coefficient on foreign share.

As noted in section 3 our instrumental variables use interaction terms between source-region macroeconomic and policy shocks and specific universities' and fields' historical dependence on students from those regions. One criticism of this list of instruments is that the past composition of graduate students in a department may have an impact on its publication output today. One potential mechanism is that many former graduate students become university faculty, so the current composition of faculty will reflect the historical composition of Ph.D. students.[13] To address this, we directly control for departmental resources (including faculty salaries) in specifications 3a and 3b. The effect of doctoral students on knowledge production is slightly diminished after introducing controls for R&D expenditures, but the estimated positive contributions of both foreign and domestic doctoral students survive this check. R&D spending is associated with increased knowledge output, while physical plant and equipment expenditures show a negative association. Controls for R&D expenditures appear to make little difference to the estimated foreign and domestic student productivities, so we omit these possibly endogenous controls in all subsequent regressions.

Another issue with our IV strategy is that the hypothesis of no over-identification can be rejected with a Sargan test at the 1% level. We therefore use a much smaller sub-set of instruments in regressions 4a and 4b. We only use a few plausibly exogenous and most powerful instruments: government policies restricting study-abroad in China, Eastern Europe and Russia, and exchange-rate movements in South Asia, Middle East and Africa (all interacted with university and field exposure to these regions). This limited set of instruments still predict foreign enrollment share and total enrollment well in the first stage, yet is unlikely to suffer from over-identification bias as its Sargan-test p-value is 0.17.

Limiting the set of instruments actually increases the estimated foreign-student contribution to knowledge output. Each additional foreign student is now associated with 1.7 extra publications (and 43 extra citations), which translate into elasticities of 0.5-0.6. The foreign productivity is significantly larger than that of American students. The increase in the estimated foreign contribution to knowledge in this specification may be attributable to heterogeneity in the type of enrolled student identified by this smaller set of instruments. The limited set of instruments identifies fluctuations in enrollment by talented students constrained from study abroad by either state restrictions or a lack of international purchasing power. These regressions reveal that such students affected U.S. scientific progress markedly.

Yet another potential issue with our IV strategy is that we use foreign macro and policy shocks to instrument both total enrollments and the foreign share. Regressions 5a and 5b thus add U.S. regional GDP movements (specifically, averages of gross state product (GSP) within regions) to the set of instruments used in 4a and 4b. We use regional rather than national incomes because economic fluctuations likely affect regional student supply but do not directly impact scientific progress nationwide. The estimates of foreign-student productivity remain qualitatively and quantitatively very similar after the inclusion of the U.S. regional instruments.

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[13] However, inference is based only on changes in publications over time within a department in these fixed-effects specifications. So this argument raises a concern for our IV strategy only when departments

Taken together, the results in Tables 2a and 2b suggest that both foreign and domestic doctoral students contribute to the production of publications at science and engineering departments, and the marginal contribution of foreign students is significantly larger than that of Americans. A 10% increase in foreign enrollment leads to a 2-6% increase in publications and citations at that department. OLS estimates of the impact of PhD students are biased downward, particularly for foreigners. As discussed in section 3a, this is consistent with crowding out of international talent by U.S. talent when a department becomes more attractive.

5b. Heterogenous Effects across Time and Universities

Table 3 explores heterogeneity in the productivity effects of foreign and domestic students over time and across different types of universities. In the early period (1973-1986) there is no significant difference between domestic and foreign students in terms of relative productivity. It is not until the late period, 1987-1998, that the productivity of foreign students is seen to be higher. The relative quality of international candidates may have risen because departments learned over time how to identify productive students.

We define elite universities as those selective institutions that maintain high test-score admission standards for their undergraduate students. In splitting the sample we chose as a criterion that the 25th percentile SAT score must be greater than 1210 (or ACT score greater than 25) for a university to be considered elite. The results show that foreign students are more productive in relative terms at elite schools. Particularly when accounting for the quality of the output, international students at elite universities are associated with very highly cited research, while their international counterparts at non-elite universities are only as productive as Americans at those schools.

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hire their own former students, a rare practice by the universities in our sample.

5c. Inferring Student-Quality Effects

We would like to examine heterogeneous productivity effects by the quality of incoming foreign doctoral students, because the optimal visa policy may be conditional on the quality of skilled immigrants. In the absence of a direct measure of student quality, we use the insight developed in the model in section 2c. Specifically, if universities trade off tuition income against research productivity, shocks to the supply of poorer students (who are differentially more reliant on scholarships) will have larger effects on knowledge creation since those shocks will pick up higher-quality students on the margin.

We implement this idea in Table 4 by defining two sets of instruments. The first includes those instrumental variables that should have neutral effects across students of varying income and wealth patterns, because they should uniformly affect the ability of all students to go abroad. These are source-country policy restrictions and changes in the number of tertiary students studying abroad (outside the United States). The second set includes those instrumental variables that affect students' ability to bear the *monetary* cost of studying in the United States. Changes in exchange rates and in GDP per capita (in non-OECD countries) will affect study-abroad decisions for the set of students paying for a U.S. education.

The idea we are trying to capture is that "pay neutral" shocks should have little effect on the quality distribution of graduate students, while positive "ability to pay" shocks could lower the average quality of students. The set of compliers in the IV regressions with instruments that affect "ability to pay" are more likely to be non-scholarship students. The latter set of shocks thus disproportionately shift enrollments toward lower-quality applicants, and comparing across the two types of IV regressions allows us to infer indirectly the effects of student quality on knowledge production.

As expected, comparing regressions 11a and 12a shows that the impact of international students on publications is significantly greater when the shocks select more scholarship students. For citations in cases 11b and 12b, the effect of an additional foreign student is only half as large when we identify this coefficient off shocks that send non-scholarship students. In fact, in the non-scholarship group, Americans are actually more productive than foreigners and can therefore more easily replace a foreigner who is denied entry. Thus, the research impact of visa restrictions on foreigners will crucially depend on how the restriction affects the quality margin, which in turn depends on how the immigration policy is implemented (i.e., whether the agency issuing visas screens for research ability or for 'ability to pay').

Table 5 shows that this quality difference persists at both elite and non-elite universities.[14] In contrast to the prediction of the tuition-income model in section 2c, the research-impact premium of scholarship students is no greater at non-elite universities. Complementarities in the production function (between high-quality students and other resources at elite universities) could explain this apparent discrepancy.

5d. Diversity Effects

The larger positive contribution of foreign doctoral students to knowledge creation that we estimate could be a pure nationality effect in which a department gets higher-quality students simply by drawing from a larger worldwide pool of applicants. Alternatively, it could be the effect of diversifying the production team (since foreigners are the minority in U.S. doctoral programs, which implies that adding foreigners adds to diversity within the lab in terms of background and training). Team members bringing complementary skills and training may have multiplicative effects on innovation.

Diversity has been recognized in the economic-geography literature as potentially important for productivity enhancements. Ottaviano and Peri (2006) set out a model of production in which variegated cultural groups offer differentiated services or skills. These heterogeneous skills of foreign workers complement those of native workers and raise productivity, though this gain must be set against the higher costs of multicultural communication and exchange. Alesina and Ferrara (2005) similarly argue that diversity could expand innovation and creativity by mixing a variety of abilities and knowledge. Berliant and Fujita (2004) note that research activities are especially susceptible to gains from interaction among different workers and exposure to greater varieties of ideas.[15] Niebuhr's (2006) empirical work on cultural diversity in the workforce and industrial patenting across German regions finds large positive effects of an employment diversity index based on national origins of workers, especially when conditioning on highly educated workers.

Table 6 creates a variable capturing diversity of doctoral student enrollments (a Herfindahl index of regional shares), and we find that diversity has a large positive and significant effect on publications and citations.[16] The elasticity of publications and citations with respect to diversity is about unity. In the average department (where 69 percent of students are American), replacing one in twenty U.S. students with a foreigner would result in at least 2.77 more publications. Moreover, the foreign enrollment share

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[14] Results for citations are consistent and to save space we do not report them here.

[15] A simple model of this process is in Fujita and Weber (2005), which has its antecedent in the seminal paper of growth gains from input variety set out by Ethier (1979), among others.

becomes insignificant when the diversity index is included, which suggests that improved diversity is the primary mechanism by which additional foreign students raise productivity in S&E labs. Put differently, student nationality *per se* does not matter. A larger foreign share actually reduces citations once the diversity index is added. This suggests that a worldwide regional mix of students (and not just the U.S. versus foreign mix) is a critical factor for high-quality scientific achievement of academic departments.

We also run the diversity regressions (not shown) in sub-samples of more collaborative (where larger numbers of individuals co-authoring on a project is the norm) and less collaborative fields. In that case greater regional diversity leads to higher-quality (i.e., more highly cited) research output in more collaborative fields.

6. Concluding Remarks

Research scientists in American universities continue to argue strongly that their ability to develop knowledge, raise grants, and ultimately expand technology-based innovation depends on unimpeded access to the highest-caliber graduate students they can attract from anywhere in the world. This claim is intuitively plausible but before now has not been tested carefully with micro data. In the absence of such a test such claims could legitimately be criticized for potentially mixing cause and effect: perhaps the rise in both research productivity and numbers and share of international doctoral students were simply coincident or caused by other factors. In any event these arguments have not resulted in changes in basic immigration policy with respect to foreign graduate students.

[16] The diversity measure is instrumented by the foreign macro and policy shocks. We have also tried instrumenting with the Herfindahl index of those shocks, and the results are qualitatively similar.

Thus, our purpose here was to assess the causal role of domestic and international doctoral students in the production of S&E knowledge. Using detailed data on the national origins of students, on academic research output, and exogenous variation in student – department matches, we demonstrate the existence of such causal effects. Both domestic and foreign students significantly increase the numbers of publications and citations in U.S. S&E departments. The contribution of international candidates is much larger, however. These results suggest that a 10% reduction in the foreign-student share would have reduced citations and publications by 5-6% in the average department over our time period. Interestingly, this difference in productivity emerged only in the second half of our sample. Moreover, international students are particularly beneficial in generating highly cited research at elite American universities.

Two further significant results emerged from this analysis. First, any macroeconomic shocks abroad that differentially reduce the ability of higher quality (scholarship) students to come to the United States substantially reduce the research output contributions of foreign doctoral candidates. Second, the most powerful impact of all appears to come from enrolling a greater regional diversity of students, holding constant the total number of graduate students. A 10% increase in diversity leads to a 10% rise in both publications and citations. Further, it appears that diversity is the primary mechanism driving the research contributions of doctoral students, rather than nationality *per se*.

These last two findings are of particular significance in practical terms. First, that the quality of international students has a significant impact at the margin implies that U.S. student-visa policy may be misguided if an important objective is to expand the research capacity of American universities. Rather than relying largely on a demonstration of financial wealth sufficient to support graduate study, an additional key criterion for issuing a visa could be indicators of student quality (easily measured by admission to top-ranked programs or winning scholarships) independent of assets or incomes. Second, that diversity is important could be a useful criterion for S&E departments in determining their admission decisions. Greater disparity of origins generates more research productivity, though this benefit must be weighed against any implied coordination costs associated with potential language difficulties.

To summarize, proponents of increasing the numbers of foreign-student visas seem to be correct. Those students are more productive in generating research outputs, and American students (with many other lucrative opportunities available in law, banking and medicine) may not easily substitute. These impacts grew stronger over time, suggesting that recent visa restrictions may have been particularly damaging. While it is difficult to place a dollar figure on the costs of skilled-student visa restrictions in terms of reduced innovation, the fact that the American economy is dependent on new products, new markets and innovation for growth (Freeman 2005) is strong indication that the consequences are potentially large. This problem was exacerbated to the extent that these restrictions differentially kept out students that could not pay for a U.S. graduate education or were aimed in ways that reduced the potential for building diverse student populations in laboratories. Perhaps these findings will be useful in future thinking about student-immigration policy.

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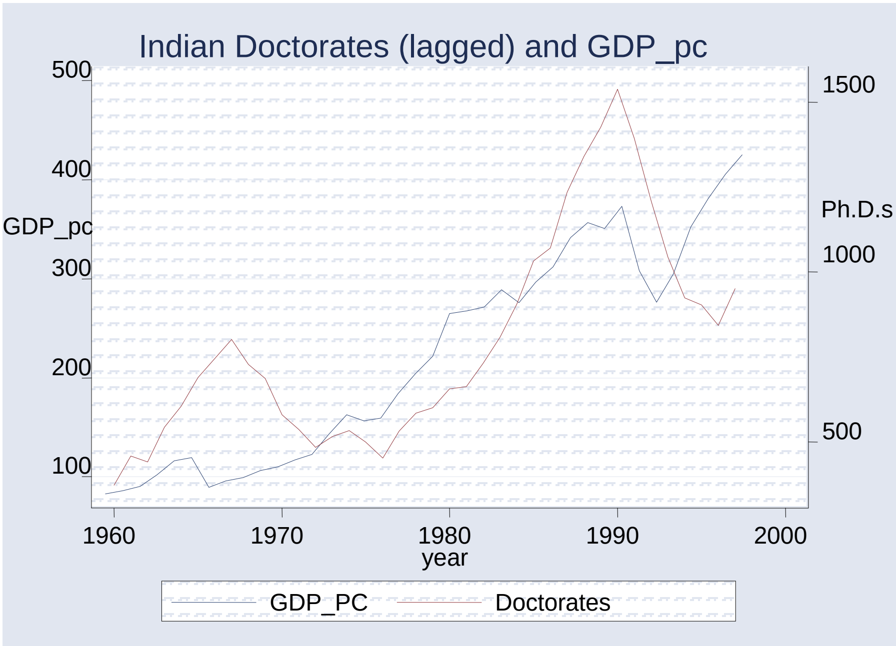
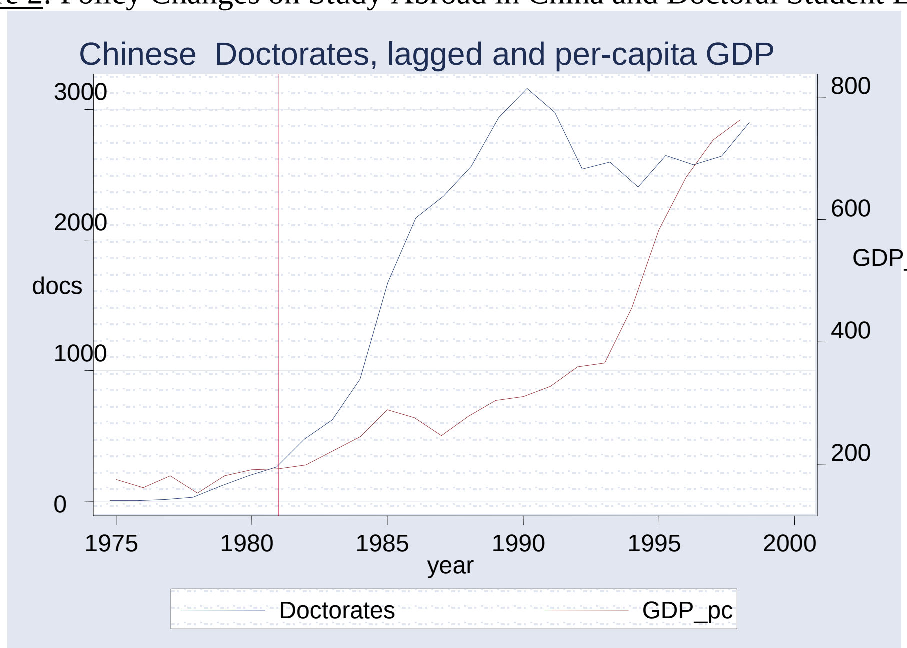
Figure 1: Time Series of Indian Doctoral Student Enrollment and GDP per Capita



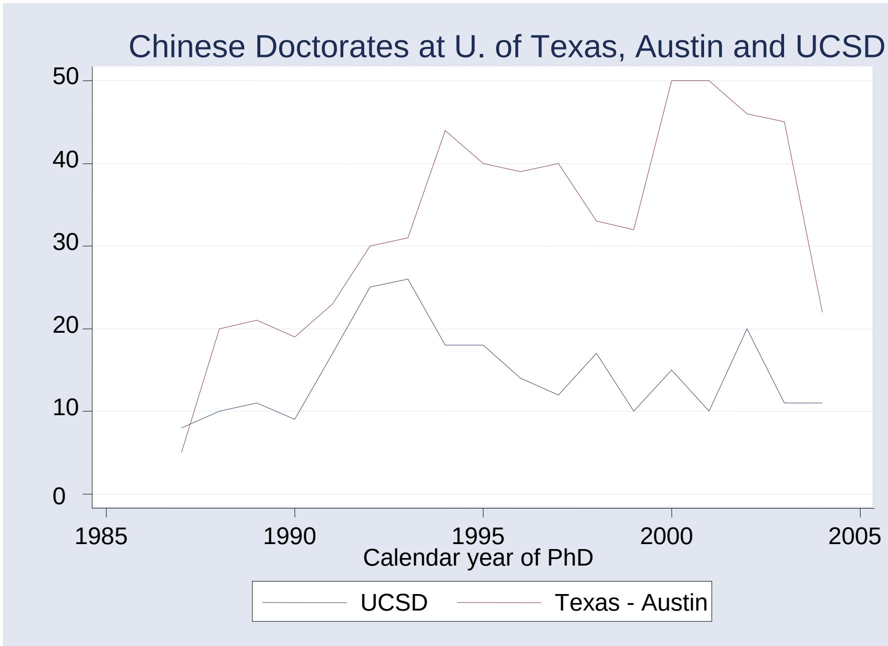
Note: ' Lagged Doctorates' is the Series 'Number of Doctoral Degrees Received by Indians' set 6 years back (i.e. around the time those doctorate recipients were enrolling in graduate school)

Figure 2: Policy Changes on Study Abroad in China and Doctoral Student Enrollment



A policy shock in 1976 (Mao's Death) and normalization of relations in 1979 paved the way for the partial (1981) and total (1984) lifting of restrictions on Chinese study abroad (Orleans 1988). GDP growth in the 1980s may explain some of the magnitude in this spike of students. Partial restrictions on study abroad were re-imposed following the 1989 Tiananmen Square Protests

Figure 3: Differential Response of Chinese Enrollment across Universities



Note: In Figures 3 and 4 "Doctorates" refers to completed doctoral candidates in the year indicated.

Figure 4: Differential Response of Chinese Enrollment across Disciplines

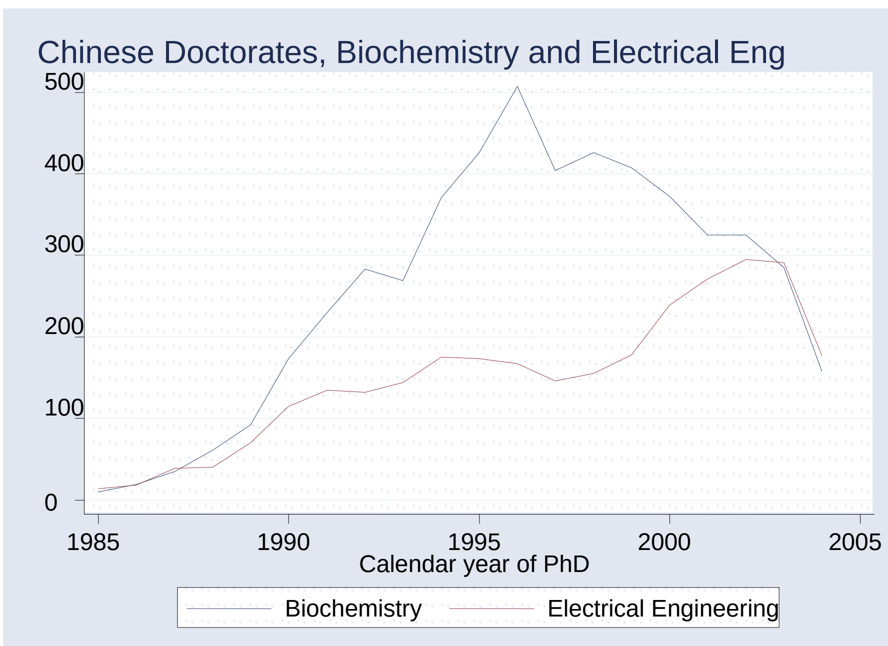


Table 1: Summary Statistics for Main Publications Dataset

Variable	Mean	Std. Dev.	Min.	Max.
Publication Counts	39.82	59.84	0	1159.00
Publication Counts - 1970's	24.86	37.71	0	526.00
Publication Counts - 1980's	38.97	56.51	0	807.00
Publication Counts - 1990's	53.97	74.54	0	1159.00
Publication Counts - Elite Univ.	50.65	69.71	0	1108.00
Publication Counts - Large Univ.	58.71	74.98	0	1159.00
Publication Citation Counts	1271.10	2796.76	0	71051.00
Citation Counts - 1970's	831.72	1814.61	0	37860.00
Citation Counts - 1980's	1272.92	2629.73	0	53257.00
Citation Counts - 1990's	1653.29	3550.14	0	71051.00
Citation Counts - Elite Univ.	2001.25	4016.76	0	71051.00
Citation Counts - Large Univ.	1995.72	3670.99	0	71051.00
PhD Enrollment - Total	42.00	53.58	0	498.00
PhD Enrollment - Foreign	14.99	22.25	0	317.00
PhD Enrollment - U.S.	27.01	37.20	0	380.00
Foreign Share in Enrollment	0.31	0.27	0	1.00
Regional Diversity Index	0.44	0.24	0	0.86
Equipment and Physical Plant Expenditures	0.74	1.28	-0.01	18.23
Other R&D Expenditures	3.52	5.95	0.00	103.53

N=57500, observations on university-field "departments"

Number of university-field groups: 2300

Table 2a. Effects of Foreign and Domestic Ph.D. Students on Department Publications

Dependent Variable: Scientific Publications per Department, Year; Estimation Method: Linear Fixed Effects

	OLS (1a)	2SLS - Full Set of Instruments (2a)	2SLS - with R&D exp. controls (3a)	2SLS - Limited set of instruments (4a)	2SLS - Adding U.S. State instruments (5a)
Total PhD Enrollment	0.1778*** (0.0055)	0.4072*** (0.0277)	0.3004*** (0.0257)	0.9063*** (0.1266)	0.9314*** (0.1048)
Foreign Share of Enrollment	-1.7201*** (0.4897)	8.1939*** (2.4165)	9.2991*** (2.7336)	53.2600*** (11.4202)	50.8565*** (9.9099)
Equip. and Phys. Plant Exp. (real $ millions, 5 yr. MA)			-0.2385*** (0.0745)		
Other R&D Exp. (real $millions, 5 yr. MA)			0.1203*** (0.0167)		
Observations	57500	57500	47959	57500	57500
No. of Field-University Pair FE	2300	2300	2214	2300	2300
First-stage statistics:					
F-stat of excluded IV on Total:		73.09	71.24	70.34	54.20
F-stat of excluded IV on Share:		76.97	58.60	68.51	48.02
Sargan Statistic:		879.28	817.93	3.52	3.91
Sargan Statistic p-value:		0.00	0.00	0.17	0.42
Sargan Statistic df:		46.00	48.00	2.00	4.00

Publication Effect of Adding one more… (at means) (1a)		Publication Effect of Adding one more… (at means) (2a)		Publication Effect of Adding one more… (at means) (4a)	
U.S Student	Non-U.S. Student	U.S Student	Non-U.S. Student	U.S. Student	Non-U.S. Student
0.482%	0.382%	0.852%	1.33%	1.165%	4.276%
0.192 pubs	0.152 pubs	0.339 pubs	0.53 pubs	0.464 pubs	1.703 pubs
$\varepsilon = 0.13$	$\varepsilon = 0.057$	$\varepsilon = 0.229$	$\varepsilon = 0.2$	$\varepsilon = 0.309$	$\varepsilon = 0.647$

Standard errors in parentheses; * significant at 10%; ** significant at 5%; *** significant at 1%

All regressions have field-university pair and year fixed effects, and university and field specific trends.

Instruments for (2a) and (3a): Set of 48 foreign regional shocks including regional max. exchange-rate, state policy, per-capita GDP, and per-capita GDP/OECD interaction, plus interactions of tertiary student count, OECD indicator and the above with university and field start-of-decade fractions, for all regions.

Instruments for (4a): 4 instruments including exch.-rate triple interactions for South Asia, Mid-east/Africa, state policy triple interactions for China and Eastern Europe

Instruments for (5a): Same as (4a) plus triple-interactions of GSP averages for E. South Central and Mountain West Regions

Table 2b. Effects of Foreign and Domestic Ph.D. Students on Citations

Dependent Variable: Citations to publications per Department, Year; Estimation Method: Linear Fixed Effects

	OLS (1b)		2SLS - Full Set of Instruments (2b)		2SLS - with R&D exp. controls (3b)	2SLS - Limited set of instruments (4b)		2SLS - Adding U.S. State instruments (5b)
Total PhD Enrollment	5.0620***		9.1681***		8.8901***	24.8138***		15.8327***
	(0.3083)		(1.5583)		(1.4506)	(6.1419)		(5.0692)
Foreign Share of Enrollment	-43.9624		635.4185***		525.2057***	1,261.9313**		1,870.7211***
	(27.4442)		(136.1542)		(154.5293)	(554.0094)		(479.2785)
Equip. and Phys. Plant Exp. (real $ millions, 5 yr. MA)					-7.6850*			
					(4.2128)			
Other R&D Exp. (real $millions, 5 yr. MA)					1.5638*			
					(0.9415)			
Observations	57500		57500		47959	57500		57500
No. of Field-University Pair FE	2300		2300		2214	2300		2300
First-stage statistics:								
F-stat of excluded IV on Total:			73.09		71.24	70.34		54.20
F-stat of excluded IV on Share:			76.97		58.60	68.51		48.02
Sargan Statistic:			459.91		412.57	12.28		26.21
Sargan Statistic p-value:			0.00		0.00	0.00		0.00
Sargan Statistic df:			46.00		48.00	2.00		4.00
	Publication Effect of Adding one more… (at means)		Publication Effect of Adding one more… (at means)			Publication Effect of Adding one more… (at means)		
	U.S Student	Non-U.S. Student	U.S Student	Non-U.S. Student		U.S. Student	Non-U.S. Student	
	0.427%	0.347%	0.306%	1.469%		1.126%	3.435%	
	5.427 cites	4.405 cites	3.891 cites	18.668 cites		14.319 cites	43.666 cites	
	ε = 0.115	ε = 0.052	ε = 0.081	ε = 0.223		ε = 0.3	ε = 0.52	

Standard errors in parentheses; * significant at 10%; ** significant at 5%; *** significant at 1%

All regressions have field-university pair and year fixed effects, and university and field specific trends.

Instruments for (2b) and (3b): Set of 48 foreign regional shocks including regional max. exchange-rate, state policy, per-capita GDP, and per-capita GDP/OECD interaction, plus interactions of tertiary student count, OECD indicator and the above with university and field start-of-decade fractions, for all regions.

Instruments for (4b): Set of 4 including exch.-rate triple interactions for South Asia, Mid-east and Africa, state policy triple interactions for China and Eastern Europe

Instruments for (5b): Same as (4b) plus triple-interactions of GSP averages for E. South Central and Mountain West Regions

Table 3.Effects of Ph.D. Students on Scientific Output in Different Eras and at Elite Universities

Dependent Variable:	Scientific Publications				Citations			
	Early	Late	Elite	Non-Elite	Early	Late	Elite	Non-Elite
	2SLS	2SLS	2SLS	2SLS	2SLS	2SLS	2SLS	2SLS
	(7a)	(8a)	(9a)	(10a)	(7b)	(8b)	(9b)	(10b)
Total PhD Enrollment	0.8597***	0.5992***	0.6519***	0.7171***	28.2815***	2.6527	11.2668	15.86***
	(0.0877)	(0.2218)	(0.2105)	(0.1440)	(4.7426)	(11.2194)	(12.5544)	(5.8614)
Foreign Share of Enrollment	10.3482	58.3362***	102.9247***	42.8021***	-736.0	1,939.3***	4,197.5**	597.7
	(13.8311)	(13.8855)	(27.8183)	(10.8185)	(748.2500)	(702.2385)	(1,658.9)	(440.3)
Observations	32200	25300	16675	40825	32200	25300	16675	40825
First-stage statistics:								
Sargan Test of Overidentification:	6.88	7.56	26.75	0.23	6.13	20.00	26.90	1.56
Sargan test p-value	0.03	0.02	0.00	0.89	0.05	0.00	0.00	0.46
Sargan test degrees of freedom	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
F-test for excluded IV on Total	112.00	26.05	31.32	44.10	112.00	26.05	31.32	44.10
F-test for excluded IV on Share	31.43	60.42	21.10	49.87	31.43	60.42	21.10	49.87
Marginal effect of U.S. Student:	0.774	0.115	-0.203	0.362	34.394	-13.454	-23.596	10.896
Marginal effect of non-U.S. Student:	1.014	1.471	2.191	1.357	17.278	31.646	74.02	24.796

Standard errors in parentheses, * significant at 10%; ** significant at 5%; *** significant at 1%

All regressions of university-field within-estimator, with year effects and field-specific trends.

Early Sample defined as 1973-1986, Late Sample defined as 1987-1998

Elite defined as institutions with 25th percentile undergraduate SAT>1210 or ACT>25

All Regressions use the same IV set as reg. (4a): exchange rate triple interactions for South Asia, Mid-east and Africa,
and state policy triple interactions for China and Eastern Europe

Table 4. Differential Effects of Paying Students vs Scholarship Students

Dependent Variable:	Scientific Publications				Citations			
Type of Shocks used to identify student supply fluctuations:	Pay Neutral		Differentially Affects Paying Students More		Pay Neutral		Differentially Affects Paying Students More	
	2SLS		2SLS		2SLS		2SLS	
	(11a)		(12a)		(11b)		(12b)	
Total PhD Enrollment	0.5957***		0.6383***		11.0104***		16.7300***	
	(0.0587)		(0.0357)		(3.2377)		(1.9394)	
Foreign Share of Enrollment	9.0283**		-11.5600***		1,076.2373***		-70.3140	
	(3.8241)		(3.5424)		(210.9702)		(192.2904)	
Observations	57500		57500		57500		57500	
No. of Field-University Pair FE	2300		2300		2300		2300	
First-stage statistics:								
F-stat of excluded IV on Total:	83.16		65.42		83.16		65.42	
F-stat of excluded IV on Share:	158.20		52.47		158.20		52.47	
Sargan Statistic:	155.74		535.12		76.60		314.79	
Sargan Statistic p-value:	0.00		0.00		0.00		0.00	
Sargan Statistic df:	13.00		27.00		13.00		27.00	
	Publication Effect of Adding one more… (at means)		Publication Effect of Adding one more… (at means)		Publication Effect of Adding one more… (at means)		Publication Effect of Adding one more… (at means)	
	U.S Student	Non-U.S. Student	U.S Student	Non-U.S. Student	U.S Student	Non-U.S. Student	U.S Student	Non-U.S. Student
	1.308%	1.835%	1.844%	1.169%	0.163%	2.131%	1.362%	1.233%
	0.521 pubs	0.731 pubs	0.734 pubs	0.465 pubs	2.072 cites	27.1 cites	17.314 cites	15.679 cites
	ε = 0.352	ε = 0.276	ε = 0.499	ε = 0.174	ε = 0.041	ε = 0.323	ε = 0.368	ε = 0.185

Standard errors in parentheses; * significant at 10%; ** significant at 5%; *** significant at 1%

All regressions have field-university pair and year fixed effects, and university and field specific trends.

Instruments for (11a,b): *Supply shifters that do not affect paying and scholarship students differentially* - triple interactions of tertiary students, all regions, plus triple interactions and levels of state policy, for China, E. Europe, W. Europe and W. Hemisphere

Instruments for (12a,b): *Supply shifters that affect paying students more* - triple interactions regional maximum exchange rate, per-capita GDP average for all regions, plus per-capita GDP average uninteracted for China, S. Asia and E. Europe.

Table 5. Differential Effects of Paying vs Scholarship Students at Elite Universities

Dependent Variable: Scientific Publications per Department, Year

Elite Status	Elite		Non-elite	
Type of Shocks used to identify student supply fluctuations:	Pay Neutral	Differentially Affects Paying Students More	Pay Neutral	Differentially Affects Paying Students More
	2SLS	2SLS	2SLS	2SLS
	(13a)	(14a)	(15a)	(16a)
Total PhD Enrollment	0.5835***	0.6955***	0.3308***	0.4964***
	(0.0772)	(0.0570)	(0.0740)	(0.0420)
Foreign Share of Enrollment	23.3807***	-13.5333**	12.6242***	-6.8480
	(6.6229)	(5.9885)	(4.2653)	(4.2142)
Observations	16675	16675	40825	40825
No. of Field-University Pair FE	667	667	1633	1633
First-stage statistics:				
F-stat of excluded IV on Total:	30.18	25.23	56.28	49.13
F-stat of excluded IV on Share:	49.14	26.99	110.16	30.82
Sargan Statistic:	134.64	221.46	74.35	352.49
Sargan Statistic p-value:	0.00	0.00	0.00	0.00
Sargan Statistic df:	13.00	24.00	13.00	27.00

	Publication Effect of Adding one more… (at means)		Publication Effect of Adding one more… (at means)		Publication Effect of Adding one more… (at means)		Publication Effect of Adding one more… (at means)	
	U.S Student	Non-U.S. Student	U.S Student	Non-U.S. Student	U.S Student	Non-U.S. Student	U.S Student	Non-U.S. Student
	0.978%	2.343%	2.028%	1.238%	0.567%	1.305%	1.389%	0.99%
	0.389 pubs	0.933 pubs	0.808 pubs	0.493 pubs	0.226 pubs	0.52 pubs	0.553 pubs	0.394 pubs
	ε = 0.262	ε = 0.354	ε = 0.549	ε = 0.184	ε = 0.152	ε = 0.197	ε = 0.376	ε = 0.148

Standard errors in parentheses; * significant at 10%; ** significant at 5%; *** significant at 1%

All regressions have field-university pair and year fixed effects, and university and field specific trends.

Instruments for (13a,15a): *Supply shifters that do not affect paying and scholarship students differentially* - triple interactions of tertiary students, all regions, plus triple interactions and levels of state policy, for China, E. Europe, W. Europe and W. Hemisphere

Instruments for (14a, 16a): *Supply shifters that affect paying students more* - triple interactions regional maximum exchange rate, per-capita GDP average for all regions, and OECD*GDP

Elite defined as institutions with 25th percentile undergraduate SAT>1210 or ACT>25

Table 6: Effects of Diversity in Student Regions-of-origin

Dependent Variable:	Publications		Citations	
	2SLS	2SLS	2SLS	2SLS
	(17a)	(18a)	(13b)	(14b)
Total PhD Enrollment	0.7710***	0.7467***	11.3855	14.1079*
	(0.1553)	(0.1608)	(8.9665)	(7.3569)
Foreign Share of Enrollment	27.2079		-3,045.4735*	
	(29.1398)		(1,682.5069)	
Diversity Index	79.1396***	101.1459***	5,889.1814***	3,425.9439***
	(27.0669)	(13.9773)	(1,562.8217)	(639.5673)
Elasticity of output with respect to Diversity:	ε = 0.80	ε = 1.03	ε = 1.86	ε = 1.08
Impact of 0.065 increase in Diversity:[a]	5.14 pubs	6.57 pubs	382.8 cites	222.69 cites
Impact of 0.035 increase in Diversity:[b]	2.77 pubs	3.54 pubs	206.12 cites	119.9 cites
Observations	49958	49958	49958	49958
R-squared				
First-stage Statistics:				
F-stat of excluded IV on Total:	42.85	42.85	42.85	42.85
F-stat of excluded IV on Share:	39.64		39.64	
F-stat of excluded IV on Diversity:	43.55	43.55	43.55	43.55
Sargan Statistic:	0.07	0.86	0.60	5.60
Sargan Statistic p-value:	0.79	0.65	0.44	0.06
Sargan Statistic df:	1.00	2.00	1.00	2.00

Standard errors in parentheses

* significant at 10%; ** significant at 5%; *** significant at 1%

All regressions have field-university pair and year fixed effects, and university and field specific trends.

In two-stage least squares regressions, total students and foreign share are instrumented with foreign shocks

Foreign Student Share is the proportion of students within a department with non-US citizenship

Diversity Index: one minus the Herfindahl index of regional concentrations of students within a department

Instruments for (2): same 4 used in regression (4a)

[a]A 0.065 increase in diversity results from 5% of students shifted from US enrollment to evenly distributed foreign enrollment, at mean foreign share

[b]A 0.035 increase in diversity results from 5% of students shifted from US enrollment to foreign enrollment concentrated in one region, at mean foreign share