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Developing science: Scientific performance and brain drains in the developing world

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ABSTRACT

Establishing a strong scientific community is important as countries develop and requires both producing and retaining of important scientists. We show that developing countries produce a sizeable number of important scientists, but that they experience a tremendous brain drain. Education levels, population, and per capita GDP are positively related to the number of important scientists born in and staying in a country. Our analysis indicates that democracy and urbanization are associated with the production of more important scientists although democracy is associated with more out-migration.

1. Introduction

Recognizing the importance of science as an economic driver, developing and developed countries alike are increasingly focusing on strengthening science.[1] With few scientists from developed countries migrating to developing countries (.2% in our data), a developing country must both (1) produce and (2) retain important scientists to achieve scientific success.

This paper studies both aspects of scientific performance in the developing world – production and retention – using data on the Institute for Scientific Information's highly cited researchers. We identify when and where these researchers were born and track their institutional affiliations over their careers. Our estimates show that 1 important scientist in 8 is born in the developing world but that there is a tremendous brain drain from the developing world, with 80% of important scientists born in the developing world now in the developed world.

The extreme size of this brain drain makes it a valuable context for studying brain drains.[2] It also makes an analysis of scientific brain drains essential for understanding the scientific performance of, knowledge production in, and knowledge diffusion to developing countries. Scientific brain drains are also interesting because exceptionally rich, longitudinal data are available on scientists' locations, making it possible to estimate brain drains over the life-cycle. By contrast, much of the existing work on brain drains (discussed below) is based on aggregate statistics.

After documenting trends in the production and retention of scientists in developing countries, we turn to the factors that are related to them. We begin by studying human capital, population, and income. At least since Romer (1986), growth economists have emphasized the importance of human capital in the production and development of new ideas. Population determines the pool of potential scientists and may affect the incentives to innovate (Jones, 1995) and small countries experience larger brain drains per capita (Beine et al., 2008; Schiff and Wang, 2008). Lastly, the income level may be related to infrastructure and resources devoted to science.

We find that large countries, countries with higher per capita income, and higher education levels all experience smaller brain drains. Large countries produce more important scientists than small countries, but not on a per capita basis. Education is also positively related to the number of important scientists born in a country. While countries with higher per capita income produce more important scientists, once education is controlled, it is not clear that they produce more per dollar of output.

Urban economists have emphasized the importance of urban agglomerations for the production and diffusion of new ideas (see Glaeser and Gottlieb, Forthcoming for a review). Another line of work has emphasized the importance of democratic institutions for growth (Acemoglu et al., 2001) and human capital accumulation (Glaeser et

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[1] On developed countries, see HM Treasury (2004, 2006); Aghion and Cohen (2004); Friedman (2005); and National Academies (2007). On developing countries see, for instance, China's 973 program (http://www.973.gov.cn/English/Index.aspx); India's 2003 Science and Technology Policy (http://www.dst.gov.in/stsysindia/stp2003.htm); and Korea's Vision 2010 (http://www.kosef.re.kr/english_new/).

[2] For instance, Docquier and Marfouk (2006) find out-migration rates of workers with a tertiary education from low income through middle income countries of 6.1–7.9%. The outmigration rates found here are equivalent to only the top handful of countries in their study, Carrington and Detragaiche (1998, 1999), and Docquier, Lowell, and Marfouk (2007). Perhaps Docquier and Rapoport's (2009) sample of medical doctors and researchers comes closest to the extreme right tail that we study. Their out-migration rates (to the US) again only approach the levels shown here for the countries with the largest brain drains.

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al., 2004). Countries that are more democratic likely restrict interactions and the exchange of ideas less.

We find that urbanization and democratic institutions are associated with the production of more important scientists. Interestingly we find that democratic institutions are associated with more out-migration and hypothesize that this relationship reflects the ability to leave countries. While disentangling specific causal mechanisms goes beyond the present analysis, these relationships hold after controlling for income, education, and population. We also explore whether our estimates are biased because democracy and urbanization are related to current investments in education and obtain reassuring results.

At least since Sjaastad (1962) economists have viewed migration as an investment in human capital. Migration has an important investment aspect for this group (indeed it may be hard for someone born in the developing world to become an important scientist without spending time in the developed world). Consequently, we expect to see a life-cycle pattern in out-migration, with more out-migration at younger ages. Our longitudinal data allow us to test this hypothesis and indicate the presence of this life-cycle pattern.

Work on brain drains has focused on how variations in the returns to skill (i) generate positive selection among migrants and (ii) induce skilled migrants to move to the countries where their skills are most highly rewarded (Borjas, 1987; Gould and Moav, 2008; Grogger and Hanson, 2011). Consistent with the first point, and as indicated, we find exceptionally high migration rates for our extremely skilled sample. The second implies that researchers should move to countries with strong research support. Indeed, among the scientists who have left developing countries, roughly 76% are in the United States, considerably more than among broader samples of even highly-skilled immigrants (e.g. Carrington and Detragaiche, 1998, 1999; Belot and Hatton, 2008; Docquier and Marfouk, 2005) which is consistent with strong research support in the United States (National Science Board, 2008, p 4–41).

Our results also relate to a small body of work on international migration among scientists. Hunter, Oswald, Charlton (2009) find a brain drain among important British scientists. Ben-David (2008) studies the brain drain of Israeli scientists, arguing that out-migration is largest in the fields where compensation is lowest in Israel relative to other countries. Weinberg (2008, 2009) finds that Britain and the United States have both experienced inflows of important scientists.

An assessment of the costs and benefits of this scientific brain drain is beyond the scope of this piece but is informed by the existing literature. Early work emphasized the costs of brain drains for developing countries (e.g. Bhagwati and Partington, 1976; Bhagwati, 1977, which propose a brain drain tax). More recent work argues that the potential for out-migration can increase education, generating a brain gain.[3] Others have argued for brain gains from return migration (Domingues Dos Santos and Postel-Vinay, 2003) and knowledge diffusion (e.g. Docquier and Rapoport's, 2009). See Commander, Kangasniemi, and Winters (2004) and Docquier and Rapoport (2009) for surveys and Schiff (2005) for an opposing view. Given the high out-migrations we find, for the first mechanism to generate a brain gain, the possibility of out-migration would have to induce large investments in skill. Our finding of return migration among researchers from developing countries provides some evidence for the second mechanism.

[3] See, for instance, Mountford (1997); Stark et al. (1997, 1998); Vidal (1998); and Beine, Docquier, and Rapaport (2001). Bhagwati and Hanson (2009) contains a wide-ranging analysis of brain drains, especially from the perspective of developed countries.

Table 1
Sample sizes.

	All		Born developing	
	Number	Share of previous	Number	Share of all
Number of highly cited researchers	6625			
Has data on location and year of birth	2360	35.6%	282	11.9%
Has institutional affiliations (longitudinal self reports)	1307	55.4%	159	12.2%
	Number	Of group, share living	Number	Share of all
Has current affiliation from ISI (i.e. is alive)	6421	96.9%		
Has data on location and year of birth	2290	97.0%	273	11.9%

Note: The top panel begins with all highly-cited researchers and focuses on those who self-report their year and country of birth. As indicated, self-reported *longitudinal affiliations* are available. These cover multiple years and provide for multiple affiliations in a given year. The bottom panel focuses on living highly-cited researchers, for whom ISI provides data on *current affiliations*.

2. Data

2.1. Data on highly cited researchers

Our data cover highly-cited researchers in 21 fields from the Institute for Scientific Information's (ISI's) Highly Cited. ISI estimates that its highly cited researchers are within the top .5% of publishing researchers in their fields during three 20-year periods from 1981–2003.[4] Because of the data identification procedures, these data are best thought of as a sample of important scientists active in the late 20th and very early 21st centuries. The full data set comprises 6625 individuals.

Table 1 documents the data coverage. Of the 6625 researchers, 2360 (35.6%) self-reported information on when and where they were born and, of these, 282 (11.9%) were born in developing countries.

We require institutional affiliations to study brain drains. There are two sources of data on affiliations. ISI has data on the current (2008) affiliations of all living highly cited researchers. Two hundred and four researchers are deceased, leaving 6421 researchers who are living. Of these researchers, 2290 (97.0%) also have data on where they were born and, of these, 273 (11.9%) were born in the developing world. Here and below, we refer to these data as “current affiliations.”

Many of the researchers who reported when and where they were born also reported their current and past institutional affiliations.[5] These self-reported data are rich in two ways. First, they are longitudinal, spanning an average of 34 years per researcher.[6] Second, researchers were able to report multiple affiliations in each year, allowing us to pro-rate time across countries. We refer to these data as the “longitudinal affiliations.” It is worth noting that the data on current affiliations cover roughly twice as many people as the

[4] The 3 20-year periods are 1981–1999; 1983–2002; and 1984–2003. Additional details are available at http://hcr3.isiknowledge.com/isi_copy/howweidentify.htm.

[5] Very few researchers reported their institutional affiliation histories but not when and where they were born, presumably because the institutional affiliation histories are more time consuming to report. Among the researchers who do report institutional affiliation histories but not when and where they were born, web searches yielded little information on when and where they were born (i.e. researchers who declined to report that information to ISI do not list that information on their websites), so these researchers are excluded from the analysis.

[6] Of the 2360 researchers who report their location of birth, 1307 (55.4%) provide institutional affiliation histories. Of these researchers, 159 (12.2%) were born in the developing world. We have 5423 annual observations on these researchers born in the developing world.

longitudinal data, but only provide a single observation for each scientist.

It is natural to consider whether the self-reported data are non-random. For instance, people born in the developed world may be less likely to have a web presence or be particularly aggressive in making information on themselves available. We test whether the people who provided data are more or less likely to be in developing countries than those who do not by comparing ISI's current affiliations for people who did and did not self-report. This analysis provides no evidence that researchers living in developing countries are under-represented in our data.[7]

2.2. Other data and classification of countries

To get a sense of the factors that are related to where important scientists are born and do their work, we have obtained data on a variety of economic, demographic, and social characteristics of countries from a number of sources. Data on population and GDP were drawn from Maddison (http://www.ggdc.net/maddison/). Data on education were drawn from Barro and Lee (2000). Data on democratic institutions[8] and executive constraints[9] were obtained from Marshall and Jaggers (2000). A wide range of other economic, industrial, and technological data were obtained from the World Bank's World Development Indicators 2005. Because annual data are not available for all countries in all years, we linearly interpolate data for the years for which it is missing.

We divide the world into four groups. The first region is the "developed world". The second region is the former Communist countries. The third region is East Asia, including the People's Republic of China. The fourth region is the "rest of the developing world." [10]

Table 2
Birth countries of highly-cited researchers.

East Asia	0.0265	Total former communist	0.0340	Total rest of developing world	0.0588
Peoples Republic of China	0.0119	Hungary	0.0085	India	0.0140
Taiwan	0.0059	Poland	0.0068	Israel	0.0114
Hong Kong	0.0042	Czechoslovakia	0.0068	Argentina	0.0055
Republic of Korea	0.0021	Russia	0.0047	South Africa	0.0047
Philippines	0.0008	Romania	0.0034	Iran	0.0025
Vietnam	0.0008	Ukraine	0.0017	Mexico	0.0021
		Yugoslavia	0.0013	Turkey	0.0021
				Brazil	0.0017
				Egypt	0.0017
				Lebanon	0.0017
				Morocco	0.0017
				Venezuela	0.0013
				Colombia	0.0008
				Cuba	0.0008
				Kenya	0.0008
				Peru	0.0008

Note: One highly-cited researcher (.04%) was born in each of the following countries: Chile, Cuba, Ethiopia, Honduras, Latvia, Lithuania, Malaysia, Mauritius, Pakistan, Panama, Republic of Congo, Saudi Arabia, Singapore, Sri Lanka, Trinidad and Tobago, Tunisia, Uganda, Zimbabwe.

3. Descriptive facts about science in the developing world

We begin with a descriptive analysis of where important scientists are born and live and the scientific brain drain. We study trends over time and differences across fields.

3.1. Where highly cited researchers are born and live

Table 2 shows the share of highly cited researchers born in individual countries or regions in the developing world. A sizeable minority of highly cited researchers (11.9%) were born in the developing world. Forty-seven developing countries were the birthplace for at least 1 highly cited researcher (with data available), with at least 1% being born in each of India, the People's Republic of China, and Israel.

Table 3 shows the share of highly cited researchers living in individual developing countries in the current affiliation sample. These results differ markedly from those for where highly cited researchers were born. Whereas 1 highly cited researcher in 8 was born in the developing world, less than one highly cited researcher in 40 (2.37%) lives in the developing world (even given the expansive definition). More highly cited researchers live in Israel than any other country classified as developing (.77%), with the People's Republic of China being home to the second largest share (.3%). Only 21 developing countries are home to highly cited researchers compared to the 47 developing countries where highly cited researchers were born. The contrast between where highly cited researchers are born and where they live indicates that there is a large brain drain of important scientists from the developing world.

Table 4 provides a descriptive analysis of outmigration for the highly-cited researchers born in the developing world based on the current affiliation sample. It shows that 17% (46 researchers) were in their country of birth and 2% (6 researchers) were elsewhere in the developing world. The remaining 221 researchers (81%) were somewhere in the developed world. The third column focuses on highly cited researchers born in the developing world who are in the developed world, showing the share in each country. Over three-quarters are in the United States (172 researchers); 6.6% are in the United Kingdom (15 researchers); and 3.7% are in Canada (10 researchers).

[7] Of the 2290 researchers who self-reported data on birth locations (whether or not they reported data on current locations), the share in developing countries is .0271 (SE = .0020). Of the 4335 for whom ISI has location data who did not self-report birth information (whether or not they reported current information), the share in developing countries is .0022 (SE = .0022). The difference is .0052 with a standard error of .0041. Thus, people who self-report birth information are slightly more likely to be in developing countries, with the difference being statistically insignificant. Comparing people who self reported both birth information and current locations to those who reported neither, the people who self-reported both are .0088 more likely to be in a developing country with a standard error of .0053.

[8] Of the democracy variable, Marshall and Jaggers (2009) write, "Democracy is conceived as three essential, interdependent elements. One is the presence of institutions and procedures through which citizens can express effective preferences about alternative policies and leaders. Second is the existence of institutionalized constraints on the exercise of power by the executive. Third is the guarantee of civil liberties to all citizens in their daily lives and in acts of political participation.... The Democracy indicator is an additive eleven-point scale (0–10) (p. 13)." It is based on four underlying variables: (1) the competitiveness of executive recruitment; (2) openness of executive recruitment; (3) constraints on the chief executive; (4) competitiveness of political participation.

[9] Of the executive constraints variable, Marshall and Jaggers (2009) write, "Operationally, this variable refers to the extent of institutionalized constraints on the decision making powers of chief executives, whether individuals or collectivities. Such limitations may be imposed by any 'accountability groups'... The concern is therefore with the checks and balances between the various parts of the decision-making process. A seven-category scale is used. (pp. 23–24)." The variable is coded: (1) Unlimited Authority (there are no regular limitations on the executive's actions); (3) Slight to Moderate Limitation on Executive Authority (there are some real but limited restraints on the executive); (5) Substantial Limitations on Executive Authority (the executive has more effective authority than any accountability group but is subject to substantial constraints by them); (7) Executive Parity or Subordination (accountability groups have effective authority equal to or greater than the executive in most areas of activity). Values (2), (4), and (6) are intermediate categories.

[10] We identify the United States, Western Europe and its other "offshoots" (Australia, Canada, and New Zealand), and Japan as developed. The Former Communist countries include Russia, the other countries in the former Soviet Union, and the former Communist countries in Eastern Europe. The rest of the developing world comprises Africa, the Americas (other than the United States and Canada), Asia (excluding the former Soviet Union and Japan); and the Pacific Islands.

Table 3
Residence countries of highly-cited researchers.

Country/region	Share	Country/region	Share	Country/region	Share
East Asia	0.0070	Former communist	0.0026	Rest of developing world	0.0141
People's Republic of China	0.0030	Hungary	0.0012	Israel	0.0077
Taiwan	0.0021	Russia	0.0009	India	0.0020
Singapore	0.0009	Poland	0.0003	South Africa	0.0012
Hong Kong	0.0005	Romania	0.0002	Brazil	0.0008
Republic of Korea	0.0005			Chile	0.0006
				Mexico	0.0005
				Panama	0.0003
				Algeria	0.0002
				Turkey	0.0002
				Pakistan	0.0002
				Philippines	0.0002
				Iran	0.0002

Note: Estimates from the current affiliation sample.

Table 4
Descriptive analysis of brain drains: current locations of highly-cited researchers born in developing countries.

Current location	Number	Share	Share of outmigrants
Australia	5	1.8%	2.2%
Austria	1	0.4%	0.4%
Canada	10	3.7%	4.4%
France	8	2.9%	3.5%
Germany	4	1.5%	1.8%
Ireland	1	0.4%	0.4%
Japan	2	0.7%	0.9%
Sweden	1	0.4%	0.4%
The Netherlands	2	0.7%	0.9%
UK	15	5.5%	6.6%
USA	172	63.0%	75.8%
Country of birth (developing)	46	16.8%	
Other developing country	6	2.2%	2.6%

Note: Table analyzes highly-cited researchers born in developing countries, showing the number and share in each country or region. Estimates from the current affiliation sample.

3.2. Income

Many of the countries studied here have developed to the point where they have high incomes, so it is worth considering whether these countries should be viewed as developing. Here and below, we will measure conditions in a researcher's country of birth at age 20. We focus on per capita GDP at age 20 to capture the time that (most) researchers begin professional training in their areas of research. We first determined how many highly cited researchers born in each country turned 20 in each year. Then, for each country, we estimate the mean log difference in per capital income between that country and the United States weighted by the share of highly cited researchers born in that country turning 20 in each year.[11]

Fig. 1 shows that the share of highly-cited researchers born in a country is very strongly related to per capita GDP, although we do not claim that this relationship is causal or that what matters is income *per se*, as opposed to say education, infrastructure, or investments in science, which are themselves related income. With the exceptions of India and China, the share of highly-cited researchers born in a country is essentially zero until a country reaches 20% of the income of the United States (roughly −1.5 log points).

Because the mean highly cited researcher was born in 1945, even countries that are relatively developed today had very low incomes at the time that the highly cited researchers were beginning their professional training. Thus, per capita GDP was 30% (1.203 log points beneath) that of the United States for highly cited researchers born in the former Communist countries, 20% (1.590 log points beneath) for researchers born in the rest of the developing world; and 10% (2.266 log points beneath) for those born in developing East Asia.

3.3. Changes within the developing world

Fig. 2 studies trends within the developing world. Among scientists born in the developing world, it shows the share born in each of 3 regions, the former Communist countries; East Asia; and the rest of the developing world. The graphs show two series. The points give the share of highly cited researchers born in each region among the highly cited researchers born in the developing world in each year. The graphs also show estimates from local linear regressions along with 95% confidence intervals.

In interpreting the graphs it is important to bear in mind, that the researchers are identified based on work done between 1981 and 2003, so that researchers born earlier in the period are doing important work at a relatively old age, while researchers born later have done important work at a relatively early age. While there is a literature on the age at which people make important scientific contributions, it has focused on individual-level factors, such as the nature of work (inductive versus deductive), and field-level factors, such as knowledge accumulation and obsolescence (see Weinberg and Galenson, 2008; Jones, 2004; Jones and Weinberg, 2009 respectively), not country-level determinants. We are not aware of reasons why our sample would be biased toward or against researchers born in the various parts of the developing world in different years.

The estimates are striking. In the early years of the period, close to 60% of the highly cited researchers born in the developing world were born in the former communist countries, but that share falls to less than 20% by the 1950s. By contrast, both East Asia and the rest of the developing world grow. The share of the highly cited researchers born in the developing world who were born in East Asia increases from under 10% to over 25%. The share of the highly cited researchers born in the developing world who were born in the rest of the developing world increases from under 40% to close to 60% by the late 1950s, turning down in the most recent years. Thus, within the developing world, there has been a clear shift in where important scientists are born away from the former Communist countries and toward other areas, especially East Asia.

3.4. Specific fields

Table 5 looks at individual fields, showing the share of highly-cited researchers in the developing world by field in the current affiliation sample. The three fields with the greatest share of researchers in developing countries are computer science (8.3%); mathematics (5%); and agricultural science (4.7%). These rankings are sensible. Computer science and mathematics, both require relatively little equipment and are abstract, making them easier to do at a distance; and agricultural science is country-specific and important for developing countries (plant and animal science is also strong in the

[11] Formally, let n_t^{C20} denote the number of highly cited researchers born in country C turning 20 in year t; let $N^C = \sum_t n_t^{C20}$ denote the total number of highly cited researchers born in country C in the sample; and let $\ln\left(\frac{GDP_t^C}{GDP_t^{USA}}\right)$ denote the log difference in per capital income between country C and the United States in year t. We estimate $\sum_t \ln\left(\frac{GDP_t^C}{GDP_t^{USA}}\right)\frac{n_t^{C20}}{N^C}$, which is the mean gap in log per capita income between country C and the United States weighted by the number of highly cited researchers born in country C turning 20.

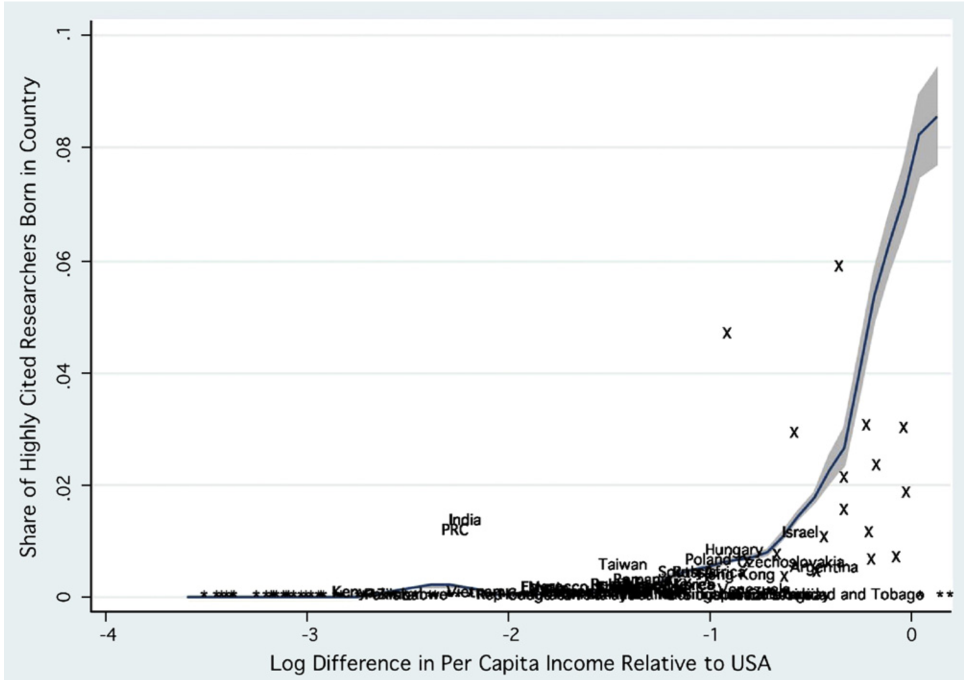

Fig. 1. GDP and the births of highly-cited researchers. The names of developing countries where highly-cited researchers were born are shown. Developing countries where no highly-cited researchers were born are indicated by *; developed countries are indicated by X (other than the United States and United Kingdom, which are off the graph). Difference in income relative to USA measured for the country of birth at the time researchers turned 20. The United States and United Kingdom are included in the local-linear regression, shown in the figure even though they are not shown on the graph.

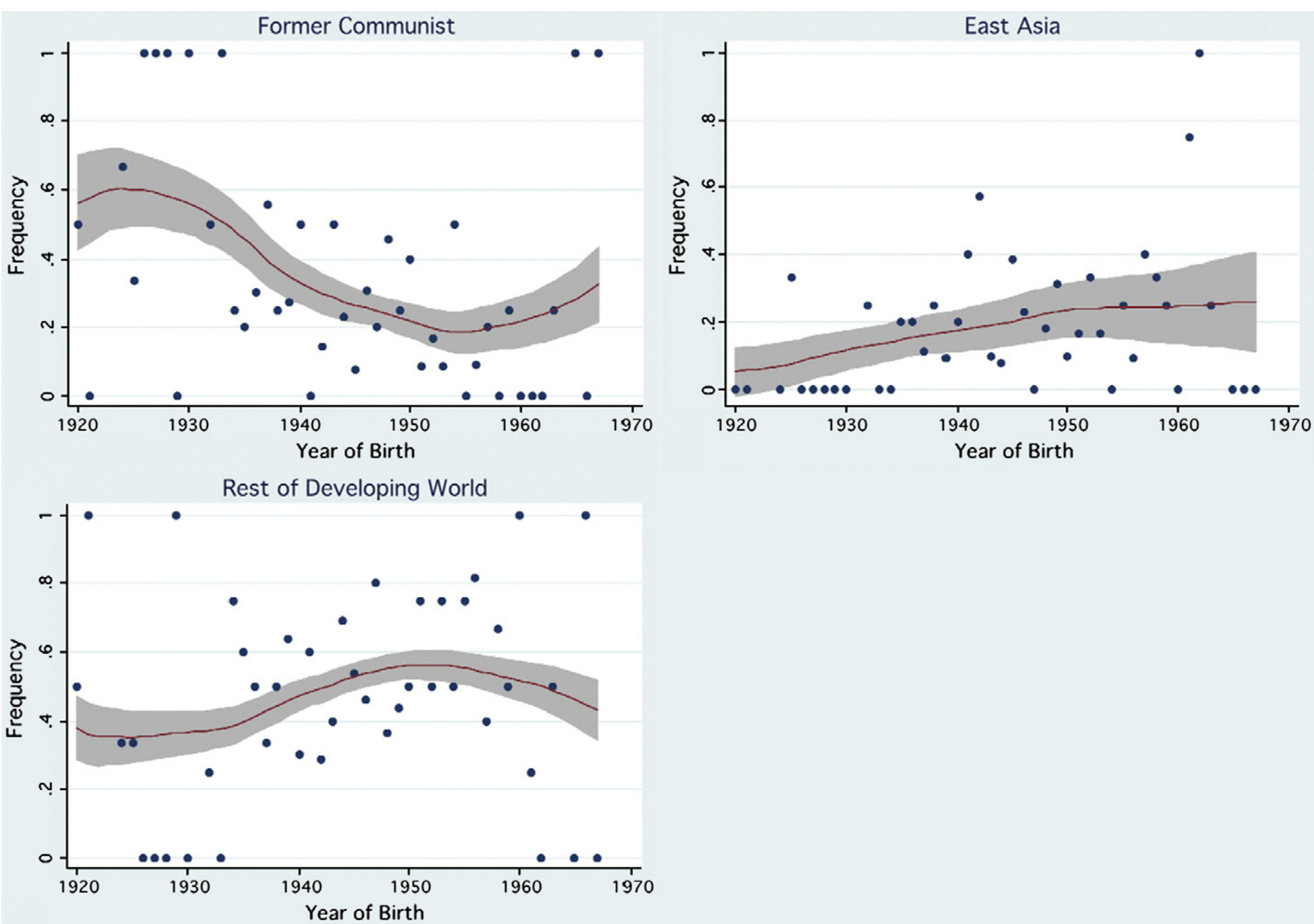

Fig. 2. Among highly cited researchers born in the developing world, the frequency born in various regions and local linear regressions summarizing the trends.

Table 5
Share of highly cited researchers living in the developing world, by field.

Field	Total developing share
Agricultural science	0.047
Biology and biochemistry	0.010
Chemistry	0.023
Clinical Medicine	0.007
Computer Science	0.083
Ecology/environment	0.026
Economics/business	0.013
Engineering	0.036
Geosciences	0.006
Immunology	0.012
Material Science	0.034
Mathematics	0.050
Microbiology	0.003
Molecular biology and genetics	0.012
Neuroscience	0.006
Pharmacology	0.029
Physics	0.033
Plant and animal science	0.031
Psychology/psychiatry	0.003
Social Sciences, General	0.006
Space Sciences	0.023

Note: Estimates from the current affiliation sample.

developing world). Despite these variations, it is clear that there are few fields with many important researchers working in the developing world.

4. Factors related to scientific performance in the developing countries

Having documented the state of science in the developing world, we now study the factors that are related to where important scientists are born and the probability they leave their birth country.

4.1. Income, population, and education

As indicated, growth economists have emphasized the importance of human capital, income, and population for the adoption and production of new technologies. To study how these (and other) factors are related to where highly cited researchers are born, we estimate Poisson regressions of the number of highly-cited researchers born in a developing country turning 20 in a given year on the log of GDP per capita, the log of population, education variables, and time trends. The unit of analysis is a country-year. We employ Poisson regressions because the estimates are efficient within the linear exponential family (Woldridge, 2002) and account for departures from a Poisson distribution by using standard errors that are boostrapped within countries.

Formally, our base specification is,

$$n_t^{C20}|X_t^C, \theta^C \sim Poisson\left(\theta^C \exp\left(X_t^C \beta\right)\right)$$

Here, n_t^{C20} denotes the number of highly cited researchers born in country C turning 20 in year t; and $X_t^C = \left[\ln\left(GDP_t^C\right), \ln\left(Pop_t^C\right), t, t^2\right]$ is a vector measuring the log of GDP per capita $\left(\ln\left(GDP_t^C\right)\right)$; population $\left(\ln\left(Pop_t^C\right)\right)$; and a quadratic in time (t and t^2). As above, we measure conditions at the time that researchers turned 20 to measure conditions at the time that most researchers would be beginning their professional training.

Given the size of the sample (both the number of countries with data and the number of researchers) and a lack of plausible instruments, we focus on random effects models (above θ^C denotes country random effects). These estimates exploit the cross-country variation in these variables as well as changes over time.[12] We are hesitant to interpret these estimates causally — unobserved heterogeneity will, if anything, lead our estimates to overstate causal effects. For instance, countries with higher income or better educated populations or more democratic institutions may well have other features that increase the production and reduce out migration of important scientists (e.g. be more stable). With this caution in mind, we provide some checks below that provide at least some reassurance that the upward bias may not be too great.

The first 2 columns of Table 6 show that the number of highly cited researchers born in a country is strongly related to both income and population. The coefficients on logged variables in a Poisson model can be interpreted as elasticities. Thus, a coefficient of 1 on population would indicate that population is unrelated to the number of important scientists born per capita. As indicated, there are reasons why large countries might produce more important scientists per capita. The coefficient on population is consistently beneath 1, but the difference is never statistically significant, indicating that on a per capita basis, large countries are comparable to small countries. Income is also strongly related to the number of highly cited researchers born in a country. Here the coefficient or elasticity is above 1, indicating the importance of income for important science.

Columns (3) through (6) include education (drawn from Barro and Lee, 2000). We measure education using the share of people who completed college and mean years of schooling. Both variables have the expected sign, but mean years of schooling is more statistically significant. Although highly-educated people are surely essential for important scientific research, the fact that highly-cited researchers are more strongly related to mean education than to the college graduation rate may indicate the importance of general investments in education, perhaps because they reflect the quality of schooling or perhaps because having a widely-educated population allows for the best students to be identified for further study. The relationships between population and income (for the country of birth at the time the researcher turned 20) on the one hand and the number of important scientists born on the other are both robust to controlling for education. The coefficient on income falls toward 1 in the sample of developing countries when mean years of schooling are included, indicating that holding human capital constant, the production of important scientists per dollar of income may be independent of per capita income.

4.2. Brain drains

Table 7 presents a number of facts about the extent to which people have left their countries of birth. These estimates are based on the longitudinal affiliation data. Letting the unit of observation be a person-year, with people included in all years for which data is available between ages 25 and 70, we estimate

$$Outmig_t^{Ci} = X_{t_{20}}^{Ci}\beta_{20} + X_t^C\beta + Z_t^{Ci}\Gamma + \theta^C + \varepsilon_t^{Ci}$$

Here, $Outmig_t^{Ci}$, denotes the share of appointments held in year t by researcher i born in country C that are outside of his or her country of

[12] We have also explored fixed effects Poisson models, which are identified from changes within countries over time. Including fixed effects increases the standard errors substantially (and, in most cases, reduces the coefficients). The estimates are largely identified off of transitory variations in the independent variables and we expect the relationship between the permanent component of income (and population and education) to be more strongly related to important science than the transitory component. Applying ordinary least squares logic, measurement error in the independent variables, which is a real concern with these data, particularly biases fixed effects estimates toward zero. Lastly, fixed effects Poisson models drop countries with no highly-cited researchers (with no positive cases), reducing the sample and especially the sample of developing countries.

Table 6
Country characteristics related to where highly cited researchers are born.

	(1)	(2)	(3)	(4)	(5)	(6)
Ln(per capita GDP)	1.464***	1.517***	1.297***	1.567***	1.001***	1.419***
	(0.230)	(0.295)	(0.217)	(0.257)	(0.271)	(0.432)
Ln(population)	0.961***	0.918***	0.898***	0.853***	0.895***	0.851***
	(0.0976)	(0.0740)	(0.108)	(0.0729)	(0.120)	(0.106)
% completed college			0.176	0.0300		
			(0.107)	(0.0666)		
Years of schooling (mean)					0.331***	0.118
					(0.116)	(0.150)
Year of birth−1975)	−0.430***	−0.455***	−0.513***	−0.517***	−0.504***	−0.515***
	(0.0235)	(0.0191)	(0.0575)	(0.0396)	(0.0599)	(0.0384)
(Year of birth−1975)^2	−0.00629***	−0.00681***	−0.00782***	−0.00788***	−0.00777***	−0.00790***
	(0.000385)	(0.000276)	(0.00110)	(0.000754)	(0.00124)	(0.000791)
Constant	−30.02***	−30.00***	−29.43***	−30.55***	−27.77***	−29.76***
	(2.464)	(2.825)	(2.367)	(2.231)	(2.820)	(3.811)
Estimation method	RE Poisson	RE Poisson	RE Poisson	RE Poisson	RE Poisson	RE Poisson
Sample	Developing	All	Developing	All	Developing	All
Observations	10563	13377	3596	4532	3485	4396
Number of countries	134	155	96	117	95	116

Note: Dependent variable is number of highly-cited researchers born in a country in a given year. Per capita GDP, population, and education measured at the time that researchers born in a given year would have turned 20 (i.e. a 20 year lead). Standard errors reported in parentheses, are clustered at the country level. Statistical significance at the 10% level indicated by *; at the 5% by **; and at the 1% level by ***.

birth (this measure implicitly assumes that time is divided equally among appointments); $X^{Ci}_{t_{20}}$ denotes the characteristics of country C at the time that researcher i turned 20 (e.g. population, income, and education levels); X^{C}_{t} denotes the characteristics of country C in the current year, t; Z^{Ci}_{t} denotes the characteristics of researcher i from country C in year t (e.g. his or her age); θ^{C} denotes country random effects; and ε^{Ci}_{t} denotes an error. Because the dependent variable varies continuously, we estimate linear models.

It is plausible that for researchers born in the developing world, spending time in the developed world (especially during training) affects the probability that a researcher makes an important scientific contribution (and gets into the sample). Insofar as this effect operates, the factors that we find are related to more outmigration (e.g. being from a very low income country) will reflect the effect of outmigration on the probability of doing important science as well as the effect of the factor (e.g. low income) on the probability of outmigration. Because

Table 7
Individual and country characteristics related to brain drains.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
		Conditions in country of birth at age 20			Current conditions in country of birth			Both current and age 20 conditions		
Age	0.113***	0.122***	0.108***	0.108***	0.121***	0.133***	0.132***	0.123***	0.137***	0.144***
	(0.0262)	(0.0313)	(0.0368)	(0.0368)	(0.0308)	(0.0356)	(0.0357)	(0.0313)	(0.0397)	(0.0375)
Age^2	−0.00223***	−0.00244***	−0.00219***	−0.00220***	−0.00235***	−0.00261***	−0.00256***	−0.00231***	−0.00273***	−0.00291***
	(0.000549)	(0.000643)	(0.000760)	(0.000761)	(0.000655)	(0.000776)	(0.000781)	(0.000671)	(0.000892)	(0.000847)
Age^3	1.44e−05***	1.59e−05***	1.46e−05***	1.47e−05***	1.53e−05***	1.71e−05***	1.66e−05***	1.47e−05***	1.96e−05***	2.10e−0 5***
	(3.75e−06)	(4.28e−06)	(5.07e−06)	(5.07e−06)	(4.55e−06)	(5.47e−06)	(5.55e−06)	(4.70e−06)	(6.59e−06)	(6.31e−06)
Characteristics of birth country when researchers turned 20										
Ln(per capita GDP)		−0.129**		−0.0731				−0.114**		−0.0421
		(0.0578)		(0.132)				(0.0517)		(0.111)
Ln(population)		−0.0272	−0.0239	−0.0336				0.184**	0.325**	0.293**
		(0.0229)	(0.0264)	(0.0292)				(0.0810)	(0.129)	(0.125)
Years of school (mean)			−0.0830**	−0.0659*					−0.0565	−0.0430
			(0.0356)	(0.0391)					(0.0461)	(0.0532)
Current characteristics of birth country										
Ln(per capita GDP)					−0.122***		−0.113***	−0.105***		−0.155***
					(0.0284)		(0.0269)	(0.0328)		(0.0526)
Ln(population)					−0.0583***	−0.0365**	−0.0508***	−0.243***	−0.356***	−0.354***
					(0.0169)	(0.0166)	(0.0161)	(0.0761)	(0.132)	(0.130)
Years of school (mean)						−0.0247**	−0.00326		−0.0371	−0.00711
						(0.0119)	(0.0116)		(0.0249)	(0.0264)
(Year of birth−1975)		0.00539	−0.0220	−0.0241	0.0176	0.0114	0.0132	0.0140	−0.0175	−0.0181
		(0.0127)	(0.0260)	(0.0270)	(0.0152)	(0.0147)	(0.0153)	(0.0144)	(0.0316)	(0.0312)
(Year of birth−1975)^2		6.17e−.05	−0.000434	−0.000511	0.000272	0.000177	0.000196	0.000173	−0.000401	−0.000444
		(0.000192)	(0.000446)	(0.000509)	(0.000233)	(0.000240)	(0.000250)	(0.000229)	(0.000571)	(0.000594)
Constant	−0.996**	0.316	−0.540	0.0688	0.710	−0.639	0.355	1.431*	−0.721	0.903
	(0.404)	(0.823)	(0.762)	(1.389)	(0.706)	(0.639)	(0.742)	(0.769)	(0.817)	(1.291)
Estimation method	Individual FE	Country RE	Country RE	Country RE	Country RE	Country RE	Country RE	Country RE	Country RE	Country RE
Observations	5423	5179	3119	3119	4637	3694	3694	4486	2283	2283
Number of country effects		36	28	28	39	34	34	36	28	28

Note: Dependent variable is the share of a researcher's affiliations in a given year that are in his or her country of birth. Estimates are based on the longitudinal affiliation sample. Sample restricted to researchers born in a developing country. Standard errors reported in parentheses, are clustered at the country level. Statistical significance at the 10% level indicated by *; at the 5% by **; and at the 1% level by ***. Country characteristics at the time that researchers born in a given year would have turned 20 are 20 year leads.

training in a developed country may be particularly important, we have re-estimated our models focusing on outmigration among people who are at least 35 years old, which yielded similar estimates.

Given that most scientists born in the developing world who leave are moving to the developed world, it seems reasonable to view time away from one's birth country as having a human capital investment component, including both training and building a professional reputation. Standard life-cycle models of human capital investment imply that investment should be greatest early in life. Column (1) focuses on individual-level determinants, showing that the share of time spent by an important scientist born in a developing country outside of his or her home country is hump-shaped over the life-cycle, peaking between ages 44 and 45 and then declining slightly. Thus, while highly cited researchers tend to spend a considerable amount of time out of their birth countries, they begin to return relatively early.

The remaining columns include income, population, and (mean years) of schooling in the country of birth. We measure all three variables at the time the person turned 20 (in columns 2–4) and in the current year (in columns 5–7). Columns 8–10 include the variables measured at age 20 and in the current year together. Higher income in the birth country is associated with less out-migration. Higher education in the country of birth is also associated with less out-migration. Although, we are reluctant to treat these relationships as causal, they are intuitive insofar as per capita income and a higher education level are associated with a better research and/or living environments. People are more likely to remain in larger countries, which is consistent with existing work (e.g. Beine et al., 2008; Schiff and Wang, 2008).

4.3. Political institutions and urbanization

As indicated, existing work provides reasons why democracy would be conducive to innovation. There is also a long line of research emphasizing the importance of urbanization for the production and diffusion of ideas. While our focus is on scientists, many of whom are affiliated with universities that are themselves geographically concentrated, urbanization may be related to geographic concentration across universities. Put differently, urbanization is likely to be related to between-university geographic concentration even if it is not related to within-university concentration. Urbanization is also likely to be related to geographic concentration of universities and other organizations engaging in research and development, including government and industrial facilities, which may produce or complement scientific research.

4.3.1. Where important scientists are born

Table 8A reports Poisson regressions of the number of highly cited researchers born in a country in each year as a function of the characteristics of the country when people turned 20. All regressions control for income and population as well as year. The first two columns include data on all countries. The second set of columns restricts the sample to developing countries. The first column in each set does not control for education, while the second column in each set does.

The top panel of Table 8A shows that countries that are more democratic or have greater executive constraints generate more highly cited researchers. The bottom panel shows that urbanization is indeed associated with the production of more important scientists, although the coefficient is not statistically significant once education is controlled.

4.3.2. Out-migration

Interestingly, the top panel of Table 8B shows that democracy and executive constraints are both associated with more out migration (these estimates are based on the longitudinal affiliation data). The fact that democratic institutions and executive constraints are associated with the production of more highly cited researchers and also more out migration suggests that the higher out migration rates are unlikely to reflect the preferences of scientists and rather reflect the ease of emigration, with less democratic countries limiting emigration. The bottom panel of Table 8B shows that urbanization is unrelated to out-migration.

4.3.3. Alternative out migration measure

The previous estimates are based on self-reported longitudinal affiliation data. Here we turn to ISI's reported data on current affiliations. While we lose the longitudinal data in the self-reports, these data contain close to twice as many researchers born in developing countries. The estimates are reported in Table 9. They are broadly consistent with the out migration results in Tables 7 and 8B.

Table 8A
Political and social indicators and the number of highly cited researchers born in countries.

	All countries	All countries	Developing countries	Developing countries
	Political indicators			
Democracy	0.0922**	0.117***	0.117*	0.150**
	(0.0433)	(0.0407)	(0.0670)	(0.0619)
Executive constraints	0.166**	0.195**	0.271***	0.314***
	(0.0736)	(0.0831)	(0.0882)	(0.108)
	Social indicators			
Urbanization	0.0219***	0.0127	0.0367***	0.0222*
	(0.00839)	(0.00954)	(0.0127)	(0.0132)
Controls for schooling		Yes		Yes
Estimation method	Random effects Poisson	Random effects Poisson	Random effects Poisson	Random effects Poisson

Note: Dependent variable is number of highly-cited researchers born in a country in a given year. Country characteristics are measured at the time that researchers born in a given year would have turned 20 (i.e. a 20 year lead). Standard errors reported in parentheses, are clustered at the country level. Estimates also control for the log of per capita GDP, the log of population, the year of birth, and (in column 2) a quadratic in age. Statistical significance at the 10% level indicated by *; at the 5% by **; and at the 1% level by ***. Each estimate is from a separate regression.

Table 8B
Political and social indicators and out-migration of highly cited researchers.

	Age 20	Age 20	Current	Current
	Political indicators			
Democracy	.0453**	0.0513***	.000498	0.000754
	(.0180)	(0.0191)	(.00348)	(0.00345)
Executive constraints	.0615***	0.0721***	−.000273	(0.00345)
	(.0214)	(0.0262)	(.00545)	(0.00524)
	Social indicators			
Urbanization	−.0000329	0.00316	.000497	0.000881
	(.00374)	(0.00476)	(.00193)	(0.00184)
Controls for schooling		Yes		Yes
Estimation method	Random effects linear model	Random effects linear model	Random effects linear model	Random effects linear model

Note: Dependent variable is the share of a researcher's affiliations in a given year that are in his or her country of birth. Estimates are based on the longitudinal affiliation sample. Sample restricted to researchers born in a developing country. Standard errors reported in parentheses, are clustered at the country level. Estimates also control for the log of per capita GDP, the log of population, the year of birth, and (in column 2) a quadratic in age. Statistical significance at the 10% level indicated by *; at the 5% by **; and at the 1% level by ***. Country characteristics at the time that researchers born in a given year would have turned 20 are 20 year leads. Each estimate is from a separate regression.

Table 9
Outmigration estimates based on current affiliation sample.

Income, population, and schooling only (included together)		
Ln(per capita GDP)	−.156*** (.0606)	−.161** (.0777)
Ln(population)	−.0177 (.0136)	−.00713 (.0176)
Years of schooling		.0197 (.0186)
Political indicators		
Democracy	−0.00824 (0.00762)	−0.00785 (0.00792)
Executive constraints	−0.0139 (0.0180)	−0.0154 (0.0188)
Social indicators		
Urbanization	−0.000178 (0.00253)	0.000256 (0.00298)
Controls Ln(per capita GDP) and Ln(population)	Yes	Yes
Controls for schooling		Yes
Estimation method	Random effects linear model	Random effects linear model

Note: Dependent variable is whether ISI reports that a researcher is affiliated with an institution outside his or her country of birth. Estimates are based on the current affiliation sample. Sample restricted to researchers born in a developing country. Standard errors reported in parentheses, are clustered at the country level. Estimates also control for the log of per capita GDP, the log of population, and year. Statistical significance at the 10% level indicated by *; at the 5% by **; and at the 1% level by ***. Aside from the top panel, which includes all variables together, each estimate is from a separate regression.

4.3.4. Other variables

We have explored a wide range of other economic and social indicators. We find a strong relationship between the production of important scientists and the aspects of trade that are likely to be associated with knowledge flows. Controlling for population, education, and income, countries with more imports and exports of manufactures and royalty payments and receipts produce more important scientists. By contrast, countries that export more raw materials produce fewer important scientists. Countries that have more royalty payments or receipts also experience smaller brain drains.

We find that countries where a greater share of manufacturing value added is in machinery manufacturing and less is in food and tobacco manufacturing produce more important scientists. We also find that fewer important scientists are born in countries with high child mortality. Neither these industrial mix variables nor child mortality are related to out-migration. Other variables, including the diffusion of technologies (measured by the use of telephones, air transportation, and energy use) and indicators of the treatment of women (the gender gaps in employment, mortality, and literacy) are not systematically related to either the number of highly cited researchers born in a country or the out-migration of highly-cited researchers.

4.3.5. Causality

These results show that holding income, population, and education constant, democracy and urbanization are all related to scientific performance. While the estimates control for population, income, and education, we are concerned that they may overstate causal effects because they are related to investments in science or education.

It is possible to check the extent to which democracy and urbanization are related to current investments in education by regressing current school enrollment (as a measure of current investment) on them. The estimates are reported in Table 10. Here we have combined democracy and executive constraints into an index. The first column, which includes no controls, shows urbanization is related to enrollment in a way that would bias our previous estimates upward, but no significant relationship for democracy and executive constraints. Column (2) includes per capita GDP as a control. The estimates in Tables 8A, 8B, 9, and 10 will only be biased upward if the variables of interest are related to investments in science and education conditional on current schooling. Column (3) also includes mean schooling as a control variable, which is a stringent test, asking if the variables of interest are related to investments in education beyond what one would expect given the current level of schooling. In this specification, the coefficient on urbanization falls and becomes statistically insignificant. While we are cautious in concluding that our estimates are not biased by either reverse causality or a correlation between the independent variables and investments in science or education, these estimates provide at least some reassurance.

Table 10
Indicators and investments in schooling.

	School enrollment	School enrollment	School enrollment
	Political indicators		
Democracy + executive constraints	0.141 (0.592)	0.232 (0.514)	0.453 (0.595)
	Social indicators		
Urbanization	1.511*** (0.250)	0.725*** (0.270)	0.209 (0.306)
Controls for GDP per capita		Yes	Yes
Controls for mean years of schooling			Yes
Estimation method	Random effects linear model	Random effects linear model	Random effects linear model

Note: Dependent variable is school enrollment. Standard errors reported in parentheses, are clustered at the country level. Statistical significance at the 10% level indicated by *; at the 5% by **; and at the 1% level by ***. Each estimate is from a separate regression.

5. Conclusion

Achieving and maintaining a strong scientific community is important as countries develop. To be successful, developing countries must both produce and retain important scientists. We show that developing countries do produce a sizeable number of important scientists, but that they experience a tremendous brain drain. Education levels, population, and per capita GDP are positively related to the number of important scientists born in and staying in a country, although it is not clear that large or rich countries produce more important scientists per capita or per unit of output.

Our analysis relates to policy in a number of ways. First, it points to institutions – democracy and urbanization – that may help developing countries achieve a high level of scientific success, although democracy is associated with more out-migration. Work is being done on whether skilled out-migrations constitute a brain drain or a brain gain and the normative implications of the large scientific brain drain we find warrant additional research. Lastly, much of the discussion about the increasing innovative potential in the developing world focuses on the challenge it poses to the United States and Western Europe. Just as Europe almost surely benefitted from the scientific rise of the United States, we suspect that both the developing and developed worlds will ultimately benefit as science develops in the developing world.

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