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Developing Countries Face Falling Circulation Rates and Rising Migration Losses in Science

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Abstract: As universities and doctoral training expand in low- and middle-income (LMI) countries, transnational scientific mobility is rising. This trend is often framed as "brain circulation," implying a mutual exchange of talent and knowledge to the benefit of all countries involved. We track 12 million scientists over 15 years, stratified by performance, to weigh this view against the prediction from structural dependency theory that expanding scientific capacity in lower-income countries may intensify rather than attenuate the loss of top-performing talent to wealthier countries. Our findings temper the brain circulation account. Circulatory migration rates have declined over time, even as the net losses from migration for LMI countries have risen. Not one of the countries that together produce 90 percent of LMI countries' top-cited early-career scientists achieves a net migration gain relative to high-income countries. It has become more difficult for developing countries to offset migratory losses with the spillovers from circulation.

Keywords: sociology of science; high-skilled migration; human capital loss; international inequality; science of science

Reproducibility Package: All codes used in conducting this analysis are available at the OSF project repository here: https://osf.io/tkh2a/. Aggregated data are available in the same repository so that plots and analyses can be reproduced. The disaggregated data from the Web of Science as well as the augmented version from the Center for Science and Technology Studies at Leiden University are proprietary and as such cannot be shared.

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Low- and middle-income (LMI) countries have steadily expanded their scientific capacity over the past few decades, building universities, training doctoral students, and increasing publication output at rates exceeding those of countries in North America and Europe (Herman et al. 2026; Marginson and Xu 2023; Schofer, Ramirez, and Meyer 2000). This has also resulted in higher migration rates for scientists working in those countries (Akbaritabar, Theile, and Zagheni 2024; Sanliturk et al. 2023; Sugimoto et al. 2017). However, there remains some uncertainty about what this means for the overall benefits and drawbacks of international mobility.

The "brain circulation" framework holds that transnational talent flows between LMI countries and high-income (HI) countries increasingly characterize modern science as they have become more common over time (Docquier and Rapoport 2012; Saxenian 2005; Sugimoto et al. 2017). Because these flows are thought to bring positive spillovers to everyone involved, the expectation has been that increased international mobility will benefit LMI countries. However, this stands in tension with structural dependency theory, an older approach which anticipates that countries in the scientific core, largely HI countries, extract value at the expense of those in the periphery (Beigel 2014; Galtung 1971; Schott 1998). According to this view, the expansion of scientific capacity in LMI countries may only increase the rate of extraction.

Tracking the international moves of 12 million scientists over 15 years and stratifying according to career performance, we reconcile elements of these competing expectations. We show that although circulatory mobility rates are high, they have declined over this period of expanding scientific capacity in LMI countries, while the net losses from migration for LMI countries have grown, and especially among their most highly cited scientists. Although some countries compensate for their net losses to HI countries with net gains from LMI countries, this also points to the existence of nested hierarchies throughout the developing world. Some countries experience large outflows of talent without regional inflows to make up for the human capital loss.

Our findings temper the brain circulation narrative by showing that circulatory flows and net talent losses are simultaneous processes, and that the latter is concentrated precisely among the top-performing scientists whose departure may be most consequential for sending countries. Furthermore, the hierarchy we document extends the dependency tradition's recognition that the periphery is internally stratified (Galtung 1971; Wallerstein 1974) and fractally structured, in the sense that Abbott (2001) introduced, with directional talent flows among LMI countries mirroring those from LMI to HI countries.

Taken together, this suggests that the global diffusion of standardized university models and transferable credentials (Baker and Powell 2024; Schofer et al. 2021) may amplify rather than attenuate a process of extraversion (Hountondji 1990), whereby the best-performing scientists gravitate toward external sources of authority, be they more affluent countries within the south or "metropolitan centers" in the north (Connell et al. 2017). From the perspective of global south countries, these results highlight durable barriers that may restrain their ability to fully capitalize on domestic talent development (Herman et al. 2026). Whether diaspora networks fully offset these losses through other channels, such as international collaboration, knowledge transfer, or human capital formation, remains an open question (Batista et al. 2025). However, answering this question first requires establishing the direction and magnitude of transnational talent flows, which is what we do here.

Background

Talented researchers have long gravitated toward the world's leading economies, drawn by collaboration opportunities, higher compensation, and the superior training available there (Arrieta, Pammolli, and Petersen 2017; Zucker and Darby 2007). For much of the twentieth century this was described as a "brain drain" that moved the best minds from Africa, Asia, and Latin America toward the Euro-American scientific core (Das 1971; Portes 1976). These concerns emerged at a time when investments in education and research systems were intensifying around the world in an effort to turn scientific capacity into economic growth, cementing scientists' international mobility as a central policy issue (Appelt et al. 2015; Tremblay 2005; Weinberg 2011).

In recent decades the landscape has shifted. Euro-American dominance in science has given way to a more multicentric system, driven by the rise of Chinese science (Wu, Esposito, and Evans 2025; Xie and Freeman 2023) but also by growing scientific communities in countries such as Singapore, Taiwan, the United Arab Emirates, and Qatar. This expansion has standardized institutional forms and credentials across borders (Schofer 2004; Schofer et al. 2021), making scientific qualifications increasingly transferable. At the individual level, there is broad agreement that research migration can benefit scientists by matching their skills and expertise with complementary knowledge sets and facilities elsewhere (Franzoni, Scellato, and Stephan 2014; Hoisl 2007). What this rising mobility means at the country level, however, is more contested, with two research traditions generating diverging predictions.

The Brain Circulation Perspective

The brain circulation perspective holds that international talent flows are increasingly reciprocal, generating benefits for destination countries as well as for origin countries (Meyer et al. 2001; Saxenian 2005). Using longitudinal publication data to classify individual researchers into migrants, travelers, and returnees, according to the affiliations listed on their papers, large-scale bibliometric research lends some support for this narrative by showing that scientists who relocate abroad often maintain affiliations linking them to their country of origin, and many eventually return (Sugimoto et al. 2017). Country-level studies have similarly used the affiliations listed on papers to operationalize brain circulation in terms of return migration. In a bibliometric analysis of health and life scientists in Brazil, Biazoli et al. (2026) classify researchers according to their international mobility histories and find that 68 percent of the internationally mobile eventually return.

Beyond bringing back new expertise and skills, these returnees may benefit their home communities by maintaining collaboration networks abroad. Jonkers and Tijssen (2008) capture this through a coauthorship analysis of expatriate life scientists returning to China, showing how this group preserved scientific collaborations with people in their former host countries after returning. Similarly, other research shows how U.S.-trained HIV researchers returning to Africa helped boost publication outputs among non-migrant colleagues through improved access to international knowledge and connections (Fry 2023).

The brain circulation narrative also rests on additional theoretical pillars. Foundational work on diaspora networks operationalizes brain circulation through the activities of expatriates that help bridge ties between otherwise loosely connected national research and innovation systems. Drawing on survey data and qualitative interviews with expatriate scientists (Meyer 2001) and mappings of diaspora networks (Meyer and Brown 1999), Meyer and colleagues argue that highly skilled migrants contribute to their countries of origin through joint research projects, such as technology transfer, student exchanges, and professional advice (Meyer et al. 2001). In a landmark qualitative study, Saxenian (2005) similarly documents how expatriate Chinese and Indian engineers maintain entrepreneurial, professional, and institutional ties with their origin locations, which in turn helps facilitate technology transfer, knowledge diffusion, and regional upgrading in those regions.

Human capital theory further suggests that widening migration opportunities may incentivize greater educational investment in sending countries, as prospective migrants acquire skills in the hope of accessing higher-return international jobs (Stark and Wang 2002). Recent empirical work in this area shows how exogenous changes in migration opportunities increase enrollment in migration-relevant education and skill acquisition in origin countries (Batista et al. 2025).

For science specifically, however, these benefits may be overstated. Where return migration from the global north to south does occur, the resulting network gains appear to accrue more to collaborators in the host country than to those in the home country (Fry 2023). Using patent citations to estimate knowledge flows between members of the Indian diaspora in the United States and domestic Indian inventors, Agrawal et al. (2011) find that although diaspora connections facilitate knowledge diffusion, they do not fully compensate for the loss of local knowledge spillovers associated with emigration. Likewise, Gibson and McKenzie (2012), who measure diaspora engagement through surveys of highly skilled migrants' knowledge sharing, trade, and other interactions with their home countries, show that these activities offer limited substitutes for physical co-location. Nor has the expansion of the scientific workforce predicted by the human-capital incentive model (Stark and Wang 2002) translated into proportionally greater representation of LMI scientists among top-cited global talent, with the south–north gap in citation elite membership widening as the number of publishing scientists in the Global South has grown steadily (Herman et al. 2026).

To briefly sum up, brain circulation has been operationalized through a range of complementary indicators, including return migration, sustained international co-authorships, diaspora engagement, knowledge flows, and increased educational investment as response to rising migration opportunities. These studies provide important evidence for the different mechanisms through which international migration may benefit origin countries. However, they tell us little about the aggregate structure of global mobility, and specifically the direction and magnitude of transnational talent flows at the global level.

Recently, large-scale bibliometric studies have shifted attention toward these aggregate structures, using longitudinal affiliation histories to characterize flows of scientific talent, including cultural, linguistic, and prestige-related mobility patterns (Murray et al. 2023), increasing regionalization (Gomez et al. 2020), differences in regions' relative attractiveness to internationally mobile scientists (Huang et al. 2024), and the relationship between economic development and scientists' emigration rates (Sanliturk et al. 2023). However, although these studies all point to global asymmetries in international mobility, they leave open the question of which countries and regions emerge as the principal net beneficiaries and net contributors of scientific talent as research migration continues to increase.

Here, we operationalize brain circulation as a property of the global mobility system rather than focusing on individual migrants, collaborations, or diaspora networks. Compared with prior bibliometric studies, our framework addresses several sources of mobility misclassification, thereby improving the identification of permanent migration, return migration, visiting mobility, and multiple affiliations within a unified longitudinal framework (Herman 2024). Furthermore, we integrate name-based origin inferences to assess potentially censored return migration that prior studies have overlooked and evaluate the robustness of our estimates across a range of plausible classification assumptions. By so doing, we can directly determine which countries and regions emerge as the principal net beneficiaries and net contributors of scientific talent.

Structural Dependency Theory

Compared to the brain circulation perspective, the structural dependency tradition offers a less optimistic interpretation of the consequences of increasing scientific mobility. Key to this tradition is a center–periphery view of global science, in which scientists from LMI countries seek recognition and career advancement through connections with institutions in North America and Europe, thereby concentrating resources and talent in the center (Alatas 2003; Delvenne and Kreimer 2017; Hwang 2008). Drawing on evidence from scientific prizes, international student mobility, citation and coauthorship data, and surveys on scientists' conference participation, research visits, international collaborations, and perceived scientific influence and deference, Schott (1998), for instance, shows how international scientific ties become increasingly concentrated in a center–periphery structure centered on North America and Western Europe.

Empirically, this asymmetry is also visible in global mobility and collaboration rates. Pei et al. (2024) show that scientifically lagging countries produce a higher share of their output through international collaboration and have a higher proportion of mobile researchers than scientifically advanced countries, while in absolute terms the vast majority of mobility and collaboration relationships remain concentrated among a small number of wealthy nations. Studies of international coauthorship networks likewise show that, despite the rapid growth of cross-border collaboration, the global scientific network remains organized around a relatively stable core of HI countries, even as emerging economies have become increasingly integrated (Wagner et al. 2015; Wagner and Leydesdorff 2005a, 2005b).

Hountondji (1990) theorized this pattern of dependency as *extraversion*, understood as the persistent orientation of peripheral scientific communities toward external sources of authority, reflected not only in directional citation flows and converging research agendas but also in individual scientists' career strategies (Collyer 2018). Indeed, this extraversion process may find its most consequential form in LMI scientists' migratory orientation toward HI countries in pursuit of better funding, infrastructure, and access to world-leading collaborators. As Tilly (2007: 249) once put it, "mobility across boundaries does not in itself change the production of inequality, but alters who benefits from inequality." If the best-performing scientists in LMI countries are disproportionately pulled toward well-resourced institutions at the center of the global science system, the expansion of scientific capacity in the periphery may primarily expand the talent pool available to North American and European research institutions. In this reading, a growing net talent loss is the expected outcome of a system where opportunities and rewards continue to be geographically concentrated (Hountondji 1990; Schott 1998). Country-specific research on selection into high-skilled migration largely supports this expectation.

As Qin (2015) shows in a study of alumni from a leading Indian engineering university, out-migrants are positively selected on ability, while return migrants are negatively selected (see also Kerr et al. 2016). In addition, this pattern persists even when governments actively attempt to reverse it. In a study of China's Young Thousand Talents scheme, established to attract early-career expatriate STEM scientists, Shi and colleagues (2023) found that although returnees were high-caliber, their prereturn performance was below that of the top Chinese expatriates who declined offers to return.

To sum up, the structural dependency tradition predicts that even in the case of rising circulatory mobility, the net effect will be a loss of scientific talent from the LMI to HI countries, and this loss will be steepest at the top of the performance distribution. Unlike prior large-scale studies of global mobility, which generally do not distinguish mobility flows by scientific performance (Gomez et al. 2020; Huang et al. 2024; Murray et al. 2023; Sanliturk et al. 2023; Sugimoto et al. 2017), or which sample directly on performance (Ioannidis 2004; Weinberg 2011), we stratify all analyses by premigration scientific performance. By so doing, we can directly assess whether talent losses are indeed concentrated among the scientists who were most likely to have contributed to national scientific capacity had they stayed.

Importantly, however, the dependency tradition cautions against treating the periphery as a monolith. As Wallerstein (1974) argued, the world system is most meaningfully understood as a tripartite structure, with semiperipheral countries occupying an intermediate position between the core and the periphery, simultaneously losing resources to the core and extracting them from the periphery (see also Galtung 1971). If the logic of extraversion operates not only between countries in the global north and south but also within the global south itself, we would expect the same hierarchical pattern to reproduce at a smaller scale, with some LMI countries compensating for part of their migration related talent losses through intraregional mobility, while other countries may face compound losses both to the HI countries and to more affluent LMI countries.

Our study is the first to evaluate this relational prediction directly through a multiplex representation of global mobility that captures countries' simultaneous positions in mobility flows between the LMI and HI countries and among LMI countries. Combined with our novel longitudinal framework for disentangling permanent migration from circulatory mobility (Herman 2024), and our stratification by premigration scientific performance, we provide global-scale evidence to adjudicate between the circulatory mobility and structural dependency perspectives.

Data and Methods

Dataset

Our global dataset uses 17 million papers from Clarivate's Web of Science (WoS) to track the mobility of 12 million authors. Although bibliometric mobility data have limitations, they continue to offer a more comprehensive and nuanced understanding of global mobility flows than what may be collected through survey questionnaires and aggregate statistics (Appelt et al. 2015; Weinberg 2011). Specifically, we use data from an enhanced version of Clarivate's WoS, comprising the Science

Citation Index-Expanded, the Social Science Citation Index, and the Arts and Humanities Citation Index, hosted at the Center for Science and Technology Studies at Leiden University. This version features systematically cleaned reference data and provides field-normalized bibliometric indicators.

It also incorporates a high-precision, rule-based author disambiguation method (D'Angelo and van Eck 2020) that enables tracking individual scholars over time and supports comparative analyses of scientific careers across locations. This method groups publications into author-level profiles using multiple metadata features, including name variants, affiliations, email addresses, ORCIDs, co-authorships, subject categories, publication outlets, self-citations, and bibliographic coupling. To ensure high data quality, we restrict the sample to authors whose first publications appeared in 2008 or later, due to lower coverage of institutional affiliations and less consistent reporting of full-first names for authors before 2008, and whose main area of work falls within our focal fields. Specifically, we focus on scientists who started their careers between 2008 and 2015. This cut-off allows us to follow the affiliation-tenure events of all authors in the sample up to the seventh year of their publication career.

We restrict our sample to full research papers and reviews published in journals, not covering letters, editorials, comments, and other document types (see our detailed Flowchart of data inclusion and exclusion in Fig. S1 in the online supplement). Moreover, we exclude the social sciences and humanities due to lower publication frequency and limited coverage in WoS, focusing only on medical and health sciences, natural sciences, agricultural sciences, and technology fields with at least 66.6 percent reference coverage. That is, fields where at least 66.6 percent of the references listed in the bibliographies of its published papers actually appear in the database. Using Organisation for Economic Co-operation and Development (OECD)'s classification of scientific fields, this results in 21 minor scientific fields, spread across 4 major scientific fields. This leaves us with a dataset of 40.3 million disambiguated scientists, and 28.7 million papers written by them. Because mobility can only be identified in bibliometric data with authors who have at least two papers, the de facto dataset for identifying mobility is made up of 12 million authors and 17 million papers.

Performance Ranking

Using field-normalized citation scores, we rank authors by cohort (here defined as the year of their first paper) to infer their global percentile rank in cumulative citations up to the year preceding the migration event. The field-normalized citation scores are calculated by dividing raw per-paper citation scores by the mean citation counts of publications of the same document type, published in the same year and subfield (excluding self-citations). Field-normalization is based on an algorithmically constructed classification system of ~4,000 fields (Ruiz-Castillo and Waltman 2015). This enables a comparison of scientists' citation percentile ranks across fields and publication years.

To ensure that older papers are not weighed more heavily than newer ones, we use a fixed four-year citation window, inclusive of the year of publication, in the citation-percentile ranks. For a paper published in year t, we only count citations for that paper received in or before year t + 3. Importantly, we only measure authors' cumulative impact up to the year prior to the mobility event. By so doing, we ensure that migrating scientists' citation-percentile rank is not directly affected by the mobility event. This is also done for scientists who take on visiting positions. For return migrants, performance is measured as their cumulative impact up to the year prior to their return (as opposed to their first migration event).

National and Regional Classification

We report results at the national level, but we also aggregate mobility in terms of national income levels, simplifying the World Bank income group classification into a binary between HI countries and all other countries. This puts us at odds with the tripartite division that is common in the structural dependency theories that we discussed earlier. We argue this is sensible in order to facilitate the analysis. The overall number of publishing scientists, or at least the number of scientists who publish in journals that are indexed by the WoS, is much smaller in less wealthy countries (cf. Sanliturk et al. 2023). This becomes especially important as we consider top-performing scientists, where wealthy countries are represented to a disproportionate extent (Herman et al. 2026). If we restrict to countries that had at least 20 top 1 percent emigrants in the 2014–2015 cohorts, we are left with 23 HI countries, but just 3 upper middle-income countries and 2 lower middle-income countries. Combining the categories allows us to avoid small sample issues during the analysis.

Rather than predefine a tripartite structure according to income groups, we disentangle semiperiphery from periphery empirically. The analyses below distinguish countries that are disadvantaged in relation to HI countries while benefiting from other LMI countries, what Wallerstein (1974) and Galtung (1971) would call the semiperiphery, from those that are disadvantaged in relation to HI and LMI countries alike, those in the so-called periphery.

Inferring Mobility

We use a new method implemented in the R package *biblio.migration* (Herman 2024), developed in parallel with this paper, to disentangle mobility types from the affiliation data on published papers. It classifies mobility into four different types: migration, return migration, visiting migration, and multiple affiliations (see also Fig. S2 in the online supplement). The approach taken in *biblio.migration* is to parameterize three common decision points in how to treat bibliometric data, which allows us to produce estimates across 144 different parameter settings and explore the statistical multiverse behind our assumptions (Young 2018; Young and Holsteen 2017). These are discussed in more detail below.

The classification proceeds in two steps. We first estimate the start and end years for scientists' tenures at each reported affiliation. Tenure is defined as a continuous period of affiliation without interruption, similar to the meaning in phrases like "international conflict arbitration increased during their *tenure* as the UN Secretary General." Importantly, scientists can have multiple nonoverlapping tenures with the same place (e.g., Michigan from 2004 to 2007 and again from 2013 to 2022). Tenures at different institutions can also overlap in time (e.g., University of Michigan from 2004 to 2007 and Université de Lausanne from 2005 to 2008).

Identifying tenures from publication data is nontrivial for several reasons, though two are especially relevant for this analysis. First, when there are gaps in the publication record—perhaps the scholar of interest did not publish in 2017 or 2018—it results in periods during which mobility may well occur without being recorded in the data because no traces were left behind. Second, scientists may report affiliations inconsistently, continuing to list past affiliations or omitting current ones due to grant agreements or prestige considerations. Taking the data at face value can therefore bias estimates of migration, particularly for the most prolific authors. The model takes a minimal approach to dealing with these issues, allowing users to smooth erratic tenures by backfilling any gap of n_b years or less in the tenure record. We estimate tenures using 0, 1, and 2 years of backfilling. Note that there is no backfilling before the first appearance of an affiliation, so as to preserve the estimated start year.

Once tenures have been estimated, we classify mobility events according to the changes and overlaps in these tenures. Figure S2 in the online supplement visualizes the classification system. *Migration* occurs when authors move from Affiliation A to Affiliation B, while tolerating an overlap of n_o years or less between the two. We estimate tenures across models tolerating 0, 1, 2, and 3 years of overlap. Ignoring such transition periods would lead to undercounting migration events.

Return migration occurs when an author leaves their original affiliation and later returns through a subsequent migration event. To ensure fair comparisons across cohorts, we count only return events that occur within the first seven years of a career. However, the results are robust even when including all return events, regardless of timing.

Visiting migration events, which to our knowledge have not been identified with bibliometric methods before, occur when a new *Affiliation B* starts and ends in the midst of a pre-existing tenure at *Affiliation A*. These do not represent true migration events, as there is never a rupture in the affiliation from the place of origin. Instead, we believe these to be more akin to visiting researcher stays. The count of visiting migration events depends on the maximum amount of overlap n_d between the two positions, or the "duration" of the visiting position, that we will tolerate before considering it too ambiguous to count as anything other than multiple affiliations. We estimate models using a maximum duration of 3, 4, and 5 years.

Ambiguous multiple affiliations are not events in and of themselves, but instead represent situations where authors have multiple affiliations, which do not resolve themselves into any of the above-mentioned categories. At the country level this is frequently the result of having three or more country affiliations, none of which start or end at the same time. Another common situation is when scientists have multiple affiliations that last for the full career. Less common, but still present in the data, is the situation, where multiple affiliations overlap, but the overlap is too long for it to be considered a visiting migration event. We track these positions because while they are too ambiguous to be counted as mobility, they can still be expected to provide returns to the national scientific system through skill development, collaboration, and the diffusion of knowledge.

In the *Results* section, we add contextual information about these ambiguous situations by specifying the starting region for individuals who have long-lasting multiple affiliations. This on its own cannot resolve the ambiguity, but it does suggest that some interpretations of the mobility hidden within this category are less likely than others. In particular, the relative abundance of multiple affiliations that started in LMI countries, as shown in Figures 6 and 7 in the main text, suggests that the net migration we see between HI countries and LMI countries is not attributable to some tendency for authors in LMI countries to continue reporting their expired affiliations in HI countries, as that would result in censored migration events in our method. If anything, the opposite appears more likely, which would imply larger gaps than what we report below.

Right-Censoring of Migration Events

The end of our dataset in 2022 leads to a spike in ambiguous mobility events. Figure S3 in the online supplement shows a clear and dramatic rise for all cohorts in the number of ambiguous mobility events as soon as tenures reach the end of the dataset. This appears to have larger consequences for LMI to HI mobility, though the same spike is evident in HI to LMI mobility as well. We address this by taking data from the 2012 cohort and computing the percentage of new mobility events that ended up being classified as migration, visiting migration, and ambiguous multiple affiliations. We then randomly assign all censored mobility events (at the country level) with probabilities equal to the computed percentages from 2012. These imputed classifications are included in all plots.

Sensitivity of Findings to Censored Return Migration

A key limitation of our approach is that bibliometric data likely undercount return migration. Specifically, individuals who migrate before publishing their first paper are not captured as return migrants. For example, consider someone born in China who moves to the United Kingdom for a PhD and returns later to China. They would only be identified as a return migrant if they had published before leaving China, allowing us to identify their first migration event. If they started publishing only after arriving in the United Kingdom, they would be counted not as a Chinese national but as an immigrant.

Because our estimates of human capital gains and losses partly depend on accounting for positive, circulatory migration, we use name-based ethnic origin prediction to refine country-of-origin estimates and assess the implications of this limitation. To conservatively estimate the extent of censored return migration, we identify country-to-country flows where at least 75 percent of migrants share a predicted ethnicity with the destination country. Ethnicity was inferred using the name-to-ethnicity algorithm (Hafner, Peifer, and Hafner 2024), which demonstrates high parity in error rates across ethnic groups. For this analysis, we exclude ambiguous ethnicities commonly associated with multiple countries (e.g., French, German, Spanish, and British).

Figure 1 shows the 72 country-to-country migration flows (a) that have at least 10 migrants and (b) where the predicted ethnicity for at least 75 percent of the

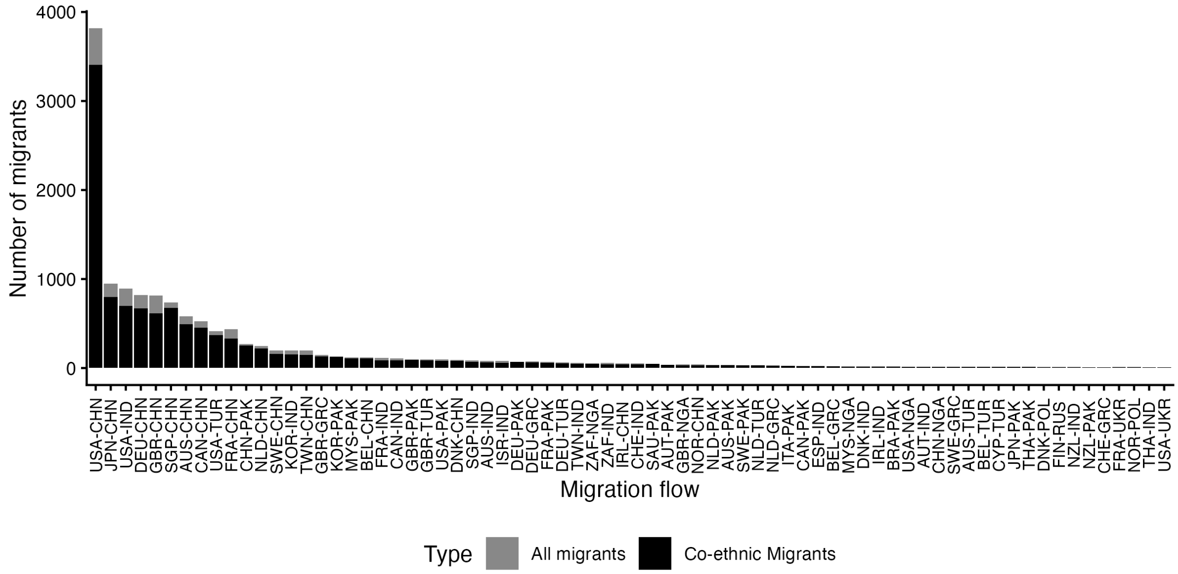

Figure 1: Incoming migration flows (labeled as sending country to receiving country) where the proportion of migrants in the 2008–2015 cohorts that have a predicted name ethnicity that matches the receiving country (e.g., Chinese and China; Greek and Greece) is greater than or equal to 0.75. The number of co-ethnic migrants within each flow (in black) is superimposed upon the total number of migrants in each flow.

migrants aligns with the destination country. The height of the bar indicates the total number of scientists in those migration flows. Scanning the list of destination countries on the x axis quickly reveals that middle-income countries such as China, India, Turkey, and Pakistan have many such flows. To account for this, we produce estimates of mobility after removing (at random) 0, 25, 50, and 75 percent of the migrants in those flows.

Multiplex Network Analysis

To characterize the importance of countries as senders and receivers within the global migration network, we adopt a multiplex network approach using the hyperlink-induced topic search algorithm. This method captures simultaneous patterns of gain and loss across multiple countries and regions, allowing us to identify not only global hierarchies but also compensatory dynamics among LMI countries. We use a degree-preserving rewiring exercise to compute p-values for our estimate of the correlation between LMI countries' hub rank (sending rank) in relation to HI countries and their authority rank (receiving rank) in relation to other LMI countries.

Similar to what one might do with layers in a multiplex network, the hub rank is computed on the subnetwork that only contains edges running from LMI countries to HI countries and edges running from one HI country to another, while the authority rank is computed on the subnetwork that only contains edges that run between LMI countries. To operationalize this approach, our rewiring exercise makes the simplifying assumption that there are three different edge types within the network: (1) edges that run between two HI countries, (2) edges that run between two LMI countries, (3) and edges that run between one HI country and one LMI country. Generating comparison networks with a similar topology means preserving nodal degrees for each of these types of edges. To generate a new network, we iterate over edge types, and within that, we repeatedly choose pairs of edges (of the same type) and swap their destination nodes. We do this until we have re-wired 10x the number of edges that exist within the focal edge type. The result is a random network with the same degree distribution across all three edge types. We generate 1,000 random networks in this way and take the 25th and 975th ordered values to define the confidence intervals.

Results

Migration Aggregated to National Income Level

We start by examining migration flows between HI countries and LMI countries for authors who published their first paper between 2008 and 2015. To distinguish permanent relocation from circulation processes, we exclude all visiting migrants and all return migrants. We also exclude scientists with longstanding multiple affiliations with at least one HI country and at least one LMI country, though our results are robust to this decision, as there are many more multiple affiliations starting in LMI countries. Counting them as potential migration events would only exacerbate the trends that we observe.

Note that Figures 2, 3, 6, and 7 all feature two panels. Panel A in each of these figures shows estimates that were produced from one particular set of parameters, which we believe makes realistic but conservative assumptions about the raw data. Panel B meanwhile shows the same estimates across all relevant parameter settings. For these four figures, we will report point estimates from the model shown in Panel A, alongside mean estimates and standard deviations from Panel B in parentheses to characterize the variation.

Figure 2 shows a clear pattern across the performance distribution, with much larger flows among the highest-performing scientists in each cohort. But it also shows that HI countries have experienced large and increasing net gains in human capital through international migration at the expense of LMI countries. Consider, for instance, that although the flow of top 1 percent scientists from HI to LMI countries has increased by 93 percent (mean = 102 percent; SD = 36 percent) from the 2008–2009 cohorts to the 2014–2015 cohorts, the reciprocal flow has grown 238 percent (mean = 230 percent; SD = 14 percent). Underscoring this trend is that the number of top 1 percent scientists who migrated from LMI to HI countries in the most recent cohort bins is 2.28 times larger than the number that moved in the other direction (mean = 3.26; SD = 0.95). These numbers likely underestimate the true difference, as they exclude all researchers with ambiguous multiple affiliations, some of whom are likely migrants. Given that scholars with ambiguous multiple affiliations originate much more frequently in LMI countries than in HI countries, including them would only exacerbate the trends we observe here (cf. Akbaritabar et al. 2024; Sanliturk et al. 2023).

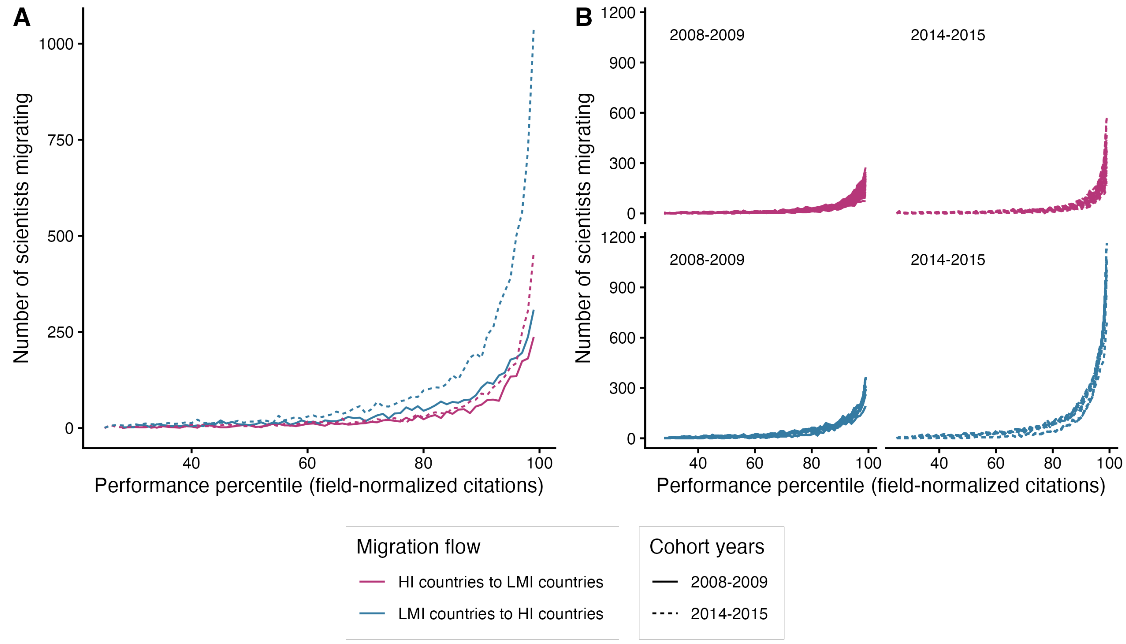

Figure 2: Burgeoning trend of brain drain. (A) Total number of authors relocating from a HI country to a LMI country and vice versa in each percentile bin of scientific performance, excluding visiting and return migration, and compared across the 2008–2009 cohorts and the 2014–2015 cohorts. These are estimated using a maximum backfill of 1 year, a maximum overlap between tenures of 2 years, and without removing any probable returners on the basis of name ethnicity. (B) The same measure for each cohort and flow from Panel A, but now estimated across a grid search of different parameter combinations over the maximum amount of backfill (0, 1, or 2 years) and the maximum amount of overlap (0, 1, 2, or 3 years) between tenures in the bibliometric data, as well as the proportion of probable return migrants that are excluded from the counts (0, 0.25, 0.5, and 0.75).

How these flows translate into net migration between HI and LMI countries can be seen in Figure 3. It plots the proportional net migration loss for LMI countries over successive cohorts, with separate lines to track scientists in different performance bins. The estimates shown in the figure make it plain that although LMI countries lose substantial amounts of talent overall, their losses come almost exclusively from among their best-performing scientists. Considering only the 2015 cohorts, for example, LMI countries had effectively net zero migration for scientists in the 0th to 89th percentile bins (mean = -0.023 percent; SD = 0.017 percent) but lost nearly 3.7 percent of their top 1 percent scientists within the first 7 years of their career (mean = 4.3 percent; SD = 0.71 percent). These losses have accelerated over time for LMI countries, and again the pattern owes to their highest-performing scientists, where the net loss for LMI countries has grown by 154 percent in our selected model in Figure 3A. Although this is on the high end of the distribution across models, averaging across all 48 models still suggests that the net losses among top 1 percent scientists nearly doubled from the 2008 cohort to the 2015 cohort (mean = 87 percent; SD= 69 percent).

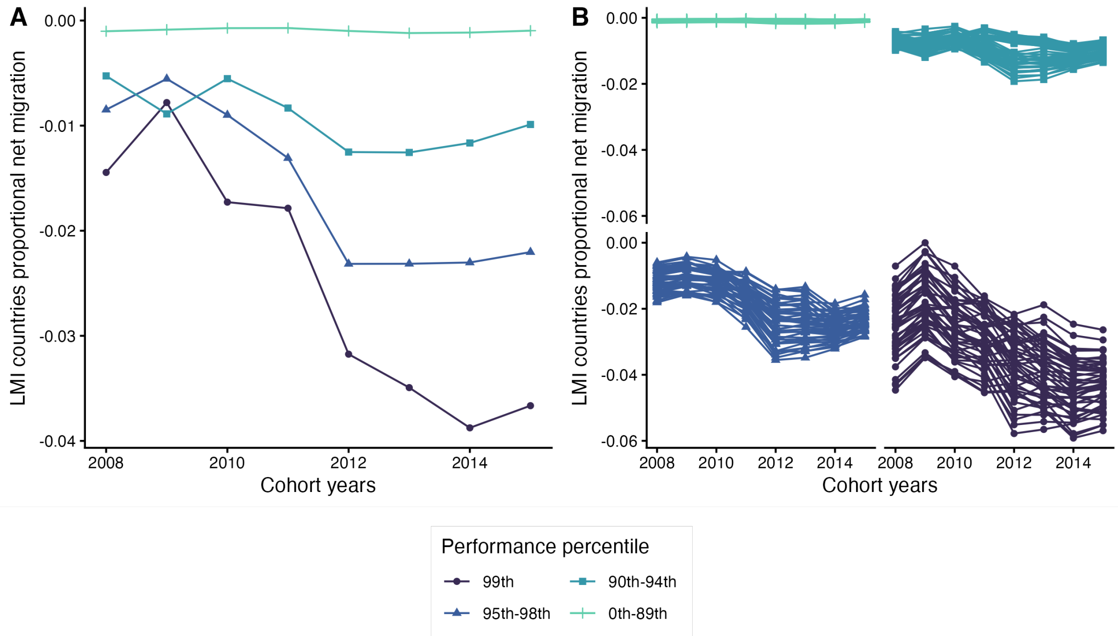

Figure 3: Increasing net losses among high performers. (A) Proportional net migration from LMI countries to HI countries over time and stratified by performance bins. These are estimated using a maximum backfill of 1 year, a maximum overlap between tenures of 2 years, and without removing any probable returners on the basis of name ethnicity. (B) The same measure for each cohort and performance bins from Panel A, but now estimated across a grid search of different parameter combinations over the maximum amount of backfill (0, 1, or 2 years) and the maximum amount of overlap (0, 1, 2, or 3 years) between tenures in the bibliometric data, as well as the proportion of probable return migrants that are excluded from the counts (0, 0.25, 0.5, and 0.75).

Migration at the Country Level

Before looking at the results for circulatory migration, let us consider some aspects of migration at the country level. It is important to note that despite the sheer scale of the scientific enterprise in the United States and China, the net losses reported in the previous section for LMI countries cannot be attributed only to the flows involving the two countries.

Figure 4 compares proportional net migration of top 1 percent scientists in the cohorts from 2014 to 2015 for the 20 economies with the most top 1 percent scientists. Each country is described with three boxplots. Our estimates of net migration among top 1 percent scientists for each country are represented using the gray boxplots. This has been further decomposed into the net migration that comes in relation to HI countries in the red boxplots, and relative to LMI countries in the blue boxplots.

LMI countries are more likely to experience net losses, as all five of the plotted LMI countries (China, Brazil, India, Malaysia, and Iran) experience notable outflows overall (4–10 percent), as shown by the gray boxplots that represent net migration overall, while among HI countries it is only France, Italy, and Spain (3–6 percent)

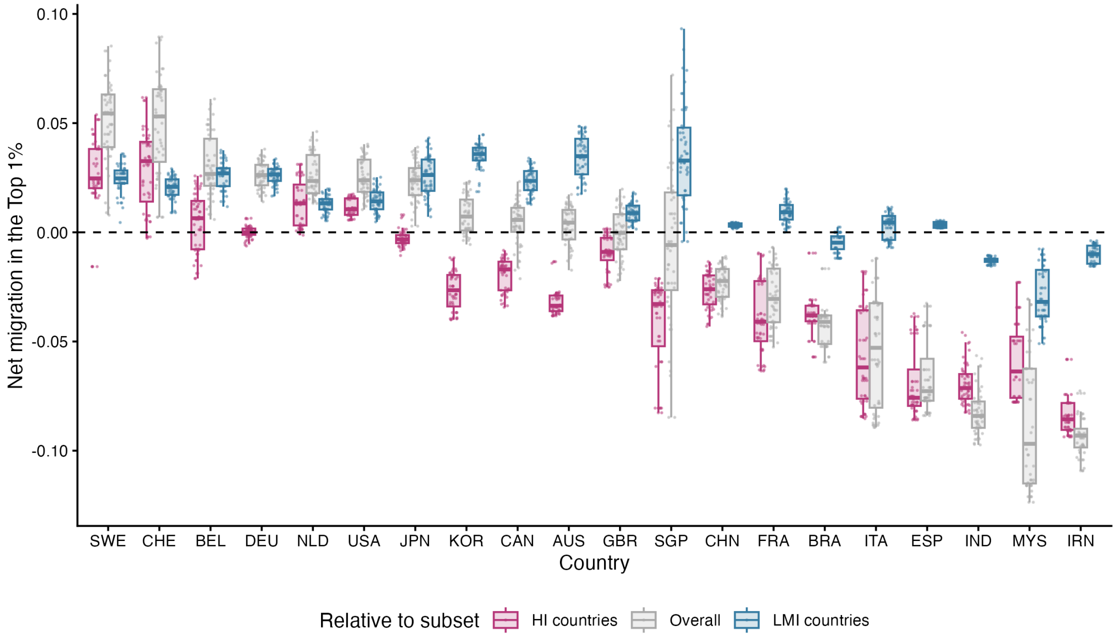

Figure 4: Net migration gains and losses (in proportions) of scientists in the top 1 percent of the 2014–2015 cohorts, for the 20 countries with the highest number of top 1 percent scientists in those cohorts. Point estimates are shown across a grid search of parameter combinations over the maximum amount of backfill (0, 1, or 2 years) and the maximum amount of overlap (0, 1, 2, or 3 years) between tenures in the bibliometric data, as well as the proportion of probable return migrants that are excluded from the counts (0, 0.25, 0.5, and 0.75). Standard boxplots are used to summarize that variation.

that suffer net losses. More interesting is the decomposition. Every LMI country in the plot is losing top 1 percent talent in relation to HI countries, while none of the HI countries is losing top 1 percent talent in relation to LMI countries. But it goes beyond this particular plot. There are seven LMI countries that together account for 90 percent of the top-cited early career scientists in the developing world—Turkey and Egypt are the two that are not already included in Figure 4. Not one of these countries avoids a net loss with regards to HI countries, something that is true not only in our preferred model, but across every one of the 48 models that we estimated. Readers can see the results for all countries in Figures S4–S13 in the online supplement, though we would caution against overinterpreting those results. Because many countries only have a small number of top 1 percent scientists in any given cohort, the additional estimates provided in the online supplement are likely volatile not only across models but also over time.

Figure 4 also points to an internal hierarchy among LMI countries, with some countries like China showing small gains through migration with respect to other LMI countries, and with others like India and Iran experiencing losses. These flows are not enough to overcome the losses that LMI countries experience in relation to HI countries—South Africa is the only country where the net gains from other LMI countries are enough to overcome the losses to HI countries among top 1 percent scientists (see Fig. S9 in the online supplement). But in general, LMI countries that lose substantial amounts of talent to HI countries are more successful in offsetting those losses with net migration from other LMI countries.

This is better understood by looking at the global migration network as a whole, as these migration flows are not independent of one another. Figure 5 shows how central LMI countries are to the global migration network in science, in terms of sending talent to HI countries (hub rank), and how central they are as a destination for talent from LMI countries (authority rank). If there is a fractal hierarchy, whereby the LMI countries that lose the most talent to HI countries are also the most successful in offsetting those losses with migrants from other LMI countries, the two centrality ranks should be correlated. Figure 5 shows a positive relationship, where LMI countries' centrality in sending talent to HI countries is correlated with their centrality in receiving talent from other LMI countries (Spearman's $\rho = 0.67$; $p < 0.001$). Descriptively, this pattern is consistent with the existence of a fractal hierarchy in science, though it is not a direct test of that claim.

Researchers working from within the brain circulation perspective have frequently suggested that the relationships between countries are driving contemporary mobility patterns in science, from proximity (Gomez et al. 2020) to shared culture and language (Murray et al. 2023), as mentioned earlier. Are they also linked to the correlation reported in the previous paragraph? Because these are dyadic characteristics in network terms, in contrast to nodal characteristics like the scale of in- and out-migration for each country—the degree—we can offer some exploratory evidence on this point by leveraging random networks.

If proximity, shared culture, shared language, or other dyadic factors played an important role in shaping the migration network in science, one would expect the correlation in the real-world network to be significantly different from the correlation in random networks wherein the connections have been reshuffled while making sure that each country continues to experience the same scale of migration. As described in *Data and Methods*, we implemented this by rewiring the edges in the global migration network in order to generate 1,000 random networks where each country sends the same number of migrants toward HI and LMI countries, respectively, but the destination country for each migrant has been randomized, removing the effect of any dyad-level factors that might be affecting the real-world network.

We find that one can obtain a correlation that is at least as extreme as the one reported above from random networks with the same degree distribution fairly frequently ($p = 0.30$). This suggests that the dyadic factors favored by the brain circulation perspective, such as proximity, shared culture, and shared language, are not necessary to explain the correlation in the real-world network. Note, however, that we cannot disentangle the effects of the various nodal characteristics from one another in these results. Specifically, the correlation is not distinguishable from a degree or scale effect, whereby LMI countries with larger scientific systems both send more talent to HI countries and receive more from other LMI countries, nor from national investments into science or other forms of network structure. As such, these results should not be read as confirmation that any one factor is responsible for the descriptive results that are consistent with a fractal hierarchy in science, only that dyadic factors are not necessary to explain them.

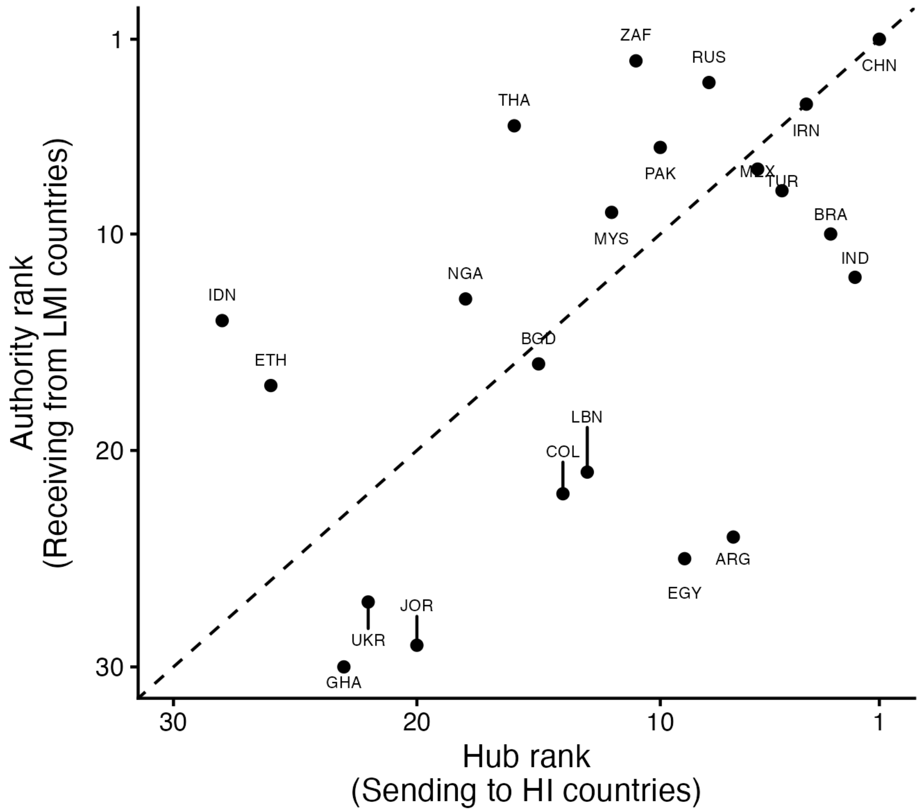

Figure 5: The centrality of LMI countries in the global scientific migration network when sending to HI countries, operationalized as their hub rank in that subgraph, plotted against their centrality when receiving from other LMI countries, operationalized through their authority rank in that subgraph.

Figure 5 also highlights the fractal structure of international inequalities. Some countries such as Russia, South Africa, Pakistan, Thailand, and Nigeria, hold network positions that are more central in receiving talent from LMI countries than they are in sending talent to HI countries, suggesting a stronger position from which to offset their net losses overall as scientific capacity continues to expand in the developing world. But others occupy less attractive positions in the network. India, Brazil, Argentina, and Egypt are all positioned much more centrally in sending talent to HI countries than they are in receiving talent from LMI countries, suggesting a double burden of talent loss without substantial offset flows. China and Iran notably sit directly on the diagonal.

Permanent and Circulatory Mobility

What about the more circulatory forms of mobility, return migration, visiting migration, and ambiguous multiple affiliations, which bring benefits to the country of origin at minimal cost? Here again the performance tier matters. Figures 6 and 7 show changes in circulatory mobility over time (comparable to Figure 3), with Figure 6 showing changes among all scientists and Figure 7 showing changes

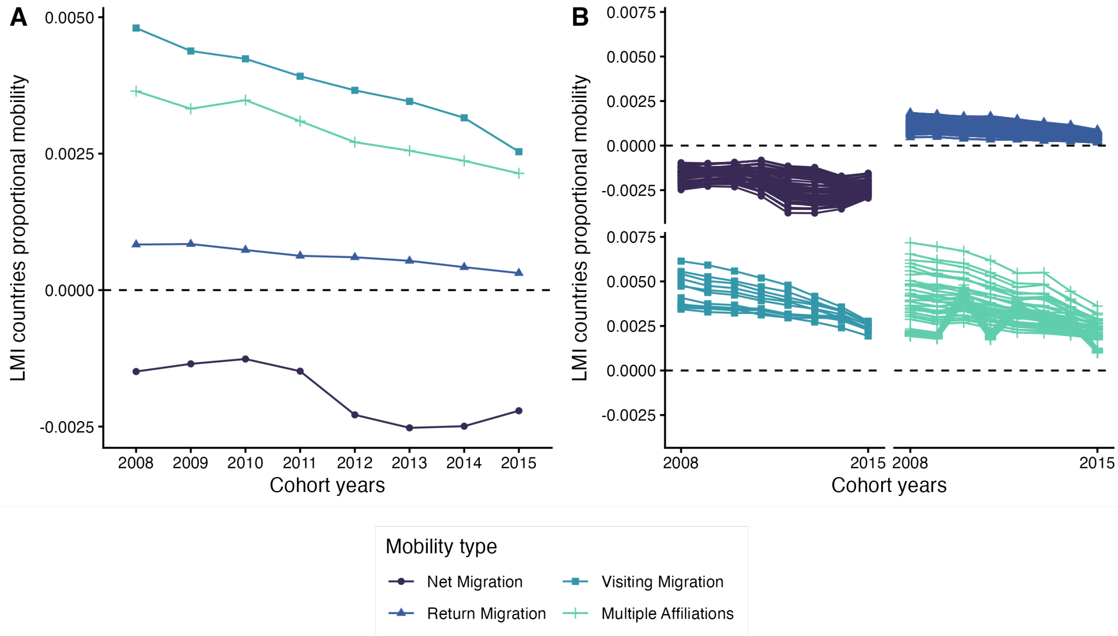

Figure 6: Circulatory migration patterns (return migration, visiting migration, and multiple affiliations) plotted alongside net migration, regardless of performance percentile. All estimates are from the perspective of LMI countries as a whole. That is, net migration represents gains/losses from the perspective of LMI countries, return migration refers to scientists taken to be returning to their LMI home countries, visiting migration refers to scientists with permanent affiliations in LMI countries who take up temporary positions in HI countries, and multiple affiliations include scientists whose first affiliation was in an LMI country but who later gain a second affiliation with a HI country. Panel A shows estimates that use a maximum backfill of 1 year, a maximum overlap between tenures of 2 years, a maximum duration of temporary positions of 3 years, and without removing any probable returners on the basis of name ethnicity. Panel B shows estimates from a grid search of parameter combinations over the maximum amount of backfill (0, 1, or 2 years), the maximum amount of overlap between tenures (0, 1, 2, or 3 years), and the maximum allowable duration for temporary positions (3, 4, or 5 years) in the bibliometric data, as well as the proportion of probable return migrants that are excluded from the counts (0, 0.25, 0.5, and 0.75).

among top 1 percent scientists. For convenience we have included trend lines for net migration.

As with our results around migration, Figure 6 shows that the overall circulatory mobility rate is low. Less than 1 percent of scientists in LMI countries were mobile with respect to HI countries in any of the three circulatory types in the 2008 cohort (mean = 0.85 percent; SD = 0.21 percent). But importantly, that figure is declining. In the 2015 cohort, the circulatory mobility rate is roughly half as large (mean = 0.42 percent; SD = 0.07 percent). This trend is not limited to one specific type of circulatory mobility. The rates of return migration, visiting migration, and multiple affiliation are all on the decline.[1]

Rates of circulatory mobility are considerably higher among high performing scientists, but it is declining among these researchers as well, as shown in Figure 7. Among the top 1 percent scientists working in LMI countries in the 2008 cohort,

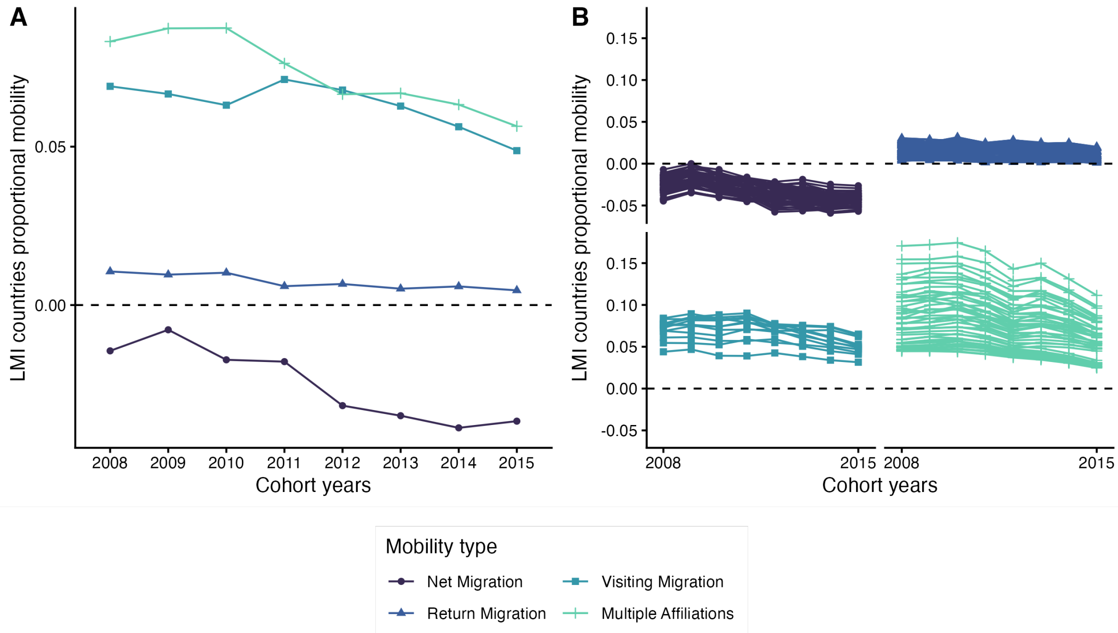

Figure 7: Circulatory migration patterns (return migration, visiting migration, and multiple affiliations) plotted alongside net migration, among top 1 percent scientists. All estimates are from the perspective of LMI countries as a whole. That is, net migration represents gains/losses from the perspective of LMI countries, return migration refers to scientists taken to be returning to their LMI home countries, visiting migration refers to scientists with permanent affiliations in LMI countries who take up temporary positions in HI countries, and multiple affiliations include scientists whose first affiliation was in an LMI country but who later gain a second affiliation with a HI country. Panel A shows estimates that use a maximum backfill of 1 year, a maximum overlap between tenures of 2 years, a maximum duration of temporary positions of 3 years, and without removing any probable returners on the basis of name ethnicity. Panel B shows estimates from a grid search of parameter combinations over the maximum amount of backfill (0, 1, or 2 years), the maximum amount of overlap between tenures (0, 1, 2, or 3 years), and the maximum allowable duration for temporary positions (3, 4, or 5 years) in the bibliometric data, as well as the proportion of probable return migrants that are excluded from the counts (0, 0.25, 0.5, and 0.75).

roughly 16.2 percent (mean = 17.2 percent; SD = 2.4 percent) had engaged in some form of circulatory mobility between LMI and HI countries in the first seven years of their career. The stark difference in the circulatory mobility rate in comparison to the full distribution highlights that, as with migration, circulatory mobility in science is largely a story about top performers. Nevertheless, by the 2015 cohort that figure had dropped by roughly a third, to 11.0 percent (mean = 11.7 percent; SD = 1.3 percent). All three forms of circulatory mobility that are measured in our models saw substantial declines over the period.

Discussion

The negative impacts that LMI countries experience from high-skilled migration are frequently offset by the benefits of more circulatory forms of international mobility, where people leave but return later on, or where people move between borders without necessarily breaking off the connection to their home countries (Cañibano and Woolley 2015; Portes 1976; Portes and Celaya 2013; Sugimoto et al. 2017; Zucker and Darby 2007). We have shown that these offsets have declined over time. Among the cohorts that span from 2008 to 2015, the proportional rate of scientists who returned home to LMI countries has declined, while the number of LMI scientists who took on visiting positions or multiple affiliations in HI countries has also declined. However, this has also coincided with rising net losses among scientists who leave and never come back. Therefore, LMI countries have larger losses to offset in the first place, and lower circulatory mobility rates to help offset them. In addition, these trends are concentrated among the best-performing scientists in these countries.

We set out to adjudicate between two accounts of what happens to global migration flows as LMI countries rapidly expand their scientific capacity. The brain circulation narrative predicts that rising mobility produces mutually beneficial exchanges through circulatory mobility and multiple affiliations. The structural dependency account in turn predicts that even in the face of rising circulatory mobility levels, the net effect will be a loss of scientific talent from LMI to HI countries, and that this loss will be steepest at the top of the performance distribution. Our findings are consistently more aligned with the second account.

East Asian economies in general and China in particular have shifted the structure of science away from its longstanding Euro-American duopoly toward a more multicentric system (Gomez et al. 2020; Montaño Ramirez and Petersen 2026; Veugelers 2010). However, this has not disrupted the traditional talent pipelines running from LMI countries to HI countries. Far from it, those migration flows have seen rapid growth, especially among the very best scientists. Nearly every LMI country continues to experience substantial losses of top talent to HI countries, and among the seven countries that together produce 90 percent of the top-cited early career scientists in the developing world, not one achieves a net gain relative to HI countries in any of the 48 models that we ran. These findings are difficult to reconcile with the brain circulation narrative's prediction of equilibrating or mutually beneficial flows, especially as circulatory mobility rates are falling over the same period of time.

Regional migration flows among LMI countries have grown over the same period, but they have done little to offset the losses to HI countries. Many countries suffer net losses to both LMI and HI countries. Among the LMI countries that are net positive, only South Africa appears to recuperate enough talent from other LMI countries to fully replace its net losses to HI countries. China sits close to net zero, despite being central to the regional migration flows among LMI countries, unable to replace talent lost to HI countries through migration alone. This all suggests that a pattern with a nested structure of migration flows undergirds the increasingly multicentric scientific system, at the largest scale with a general tendency for top talent to move from LMI to HI countries, but also with regional flows that offer relief for some countries and a double disadvantage for others.

Readers should bear in mind that our study examines the brain circulation and structural dependency perspectives by evaluating key predictions that they make about international mobility, rather than attempting to test the broader theoretical frameworks in their entirety. Although our design is suitable for testing the brain circulation perspective's prediction of circulatory mobility flows that offset permanent losses, it does not capture the downstream externalities emphasized by this perspective, such as diaspora engagement, knowledge flows through sustained collaborations abroad, or increased educational investment in response to rising migration opportunities. Our findings do not rule out such benefits, but rather suggest that if they exist, which remains to be settled for science, they are operating against the backdrop of declining circulatory mobility and rising permanent losses among the highest-performing scientists. Similarly, our test of structural dependency theory is restricted to the mobility-related implications of dependency. Specifically, we test the prediction that the persistent orientation of peripheral scientific communities toward external sources of authority, reflected in individual scientists' migration decisions, results in a net loss of scientific talent from LMI to HI countries even under rising circulatory mobility, with the steepest losses occurring among the highest-performing scientists. This focus keeps us from directly examining other mechanisms emphasized by the dependency tradition, including dependence on foreign scientific funding and research infrastructure (Miao et al. 2023), the concentration of scientific publishing and editorial gatekeeping in HI countries (Larivière et al. 2015), the growing dominance of English in scientific publishing (Amano et al. 2016), and the influence of core countries over global research agendas (Castro Torres and Alburez-Gutierrez 2022; Evans, Shin, and Ioannidis 2014; Gomez 2026; Moscona and Sastry 2025).

Add to this that our analysis is descriptive and therefore cannot distinguish the specific mechanisms that generate the observed disparities in mobility patterns or adjudicate among competing explanations for why they arise. Rather, its primary objective has been to evaluate whether the aggregate structure of global scientific mobility is more consistent with the predictions of the brain circulation or structural dependency perspectives. Still, the new methodology for identifying and classifying mobility developed for this study provides the best current accounting of circulatory mobility, as well as an improved measurement of migration in relation to earlier accounts of circulation, without sacrificing accuracy in identifying migration in relation to current state-of-the-art techniques.

Another important limitation of our study is that we do not capture short-term forms of mobility, such as exchange visits or sabbaticals, as these are not detectable through author affiliations in published papers. Although this may lead us to underestimate the extent of the LMI-HI gap in visiting migration, it does not change our main finding that LMI countries are losing far more high-performing scientists than they gain. Indeed, because a substantial portion of LMI-to-HI migration involves high-performing students pursuing MA or PhD degrees abroad (Li et al. 2019), and many of these prospective researchers have not yet published their first paper when relocating, our study likely underestimates the net migration loss for sending countries in the global south (Choudhury et al. 2023).

Our findings bolster the view of the United States and Western Europe as primary destinations for leading scientists worldwide. In this view, global south countries could benefit from improved policies and programs encouraging return migration, but such policies often fail to attract the highest-performing expatriates.

Although some global south economies have re-entry policies and schemes in place, albeit with varying success, real obstacles, including competitive compensation, state-of-the-art equipment and facilities, clear promotion pathways, and opportunities for collaboration with leading international scientists, remain in attracting the best performing expatriates (Li et al. 2019; Shi et al. 2023).

In conclusion, many researchers and policymakers have advanced an optimistic "brain circulation" narrative wherein developing and developed countries alike benefit from increased mobility (Sugimoto et al. 2017). Empirical research has given good reason for that optimism, emphasizing downstream benefits such as diaspora engagement, sustained collaborations abroad after returning, and migration-induced educational investments in origin countries. The evidence for these effects in science, it must be said, remains mixed, but the potential for these mechanisms to increase scientific capacity in developing countries is tantalizing.

However, the human capital flows in science themselves indicate that there are still reasons to be concerned. The large and growing talent flows that we document threaten to leave some countries at a substantial disadvantage in the case that the mechanisms described above do not provide enough second-order compensation. We urge the field to continue to explore the long-term impact of LMI-to-HI migration on the research activities, collaboration networks, and PhD graduation rates of the scientific communities left behind. In particular, attention must be paid to the differentiated hierarchy of talent flows among LMI countries and the distinct challenges faced by countries doubly disadvantaged by losses to both the developing and developed worlds.

Note

1 Note that the overall variation is less than it otherwise might appear in Figures 6B and 7B, as the parameter setting for the maximum duration of temporary positions mainly shuffles people between the visiting migration and ambiguous multiple affiliation classifications. There are other factors at work, but in general as one rises the other tends to fall.

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