Bigger Than You Thought: China's Contribution to Scientific Publications and Its Impact on the Global Economy

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Abstract

China's advance to the forefront of scientific research is one of the 21st century's most surprising developments, with implications for a world where knowledge is arguably "the one ring that rules them all." This paper provides new estimates of China's contribution to global science that far exceed estimates based on the proportion of papers with Chinese addresses in databases of international journals. Address-based measures ignore articles written by Chinese researchers with non-Chinese addresses and articles in Chinese language journals not indexed in those databases. Taking account of these contributions, we attribute 36 percent of 2016 global scientific articles to China. Taking account of increased citations to Chinese-addressed articles relative to the global average as well, we attribute 37 percent of global citations to scientific articles published in 2013 to China. With shares of articles and citations more than twice its share of global population or GDP, China has achieved a comparative advantage in knowledge that has implications for the division of labor and trade among countries and for the direction of research and of technological and economic development worldwide.

Key words: China National Knowledge Infrastructure, China scientific output, citation, comparative advantage, innovation, knowledge economy

JEL codes: J21, J44, O3, P5

I. Introduction

China's extraordinary economic growth since the Cultural Revolution has closely

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followed the precepts of modern economics. China shifted its economy toward markets, joined the global economy, expanded higher education and industrialized via low wage manufacturing. However, the country went beyond the standard path of development in one important way. It invested heavily in science and engineering[1] to jump from bit player to major contributor in global scientific activities. In the modern knowledge economy where scientific knowledge is arguably "the one ring that rules them all,"[2] China's new comparative advantage in the production of scientific and engineering knowledge will make it a major driver of the division of labor and trade among countries and of the direction of research and of technological and economic development worldwide.

This paper estimates China's contribution to global science based on the quantity and quality of Chinese articles in *physical sciences, engineering and mathematics*[3] journals relative to the total number of articles in those journals. The major finding is that, when properly measured to take account of articles authored by Chinese researchers at non-Chinese addresses as well as of China-addressed articles in the Scopus database, and of articles in Chinese language journals not in the Scopus database, Chinese contributions account for 36 percent of global scientific publications. This is approximately twice the standard address-based measure of papers in international scientific journals and a comparable share of global scientific citations.

The paper proceeds in four parts. Section II provides our estimates of China's share of articles in scientific journals, with the number of Chinese language articles outside the Scopus database adjusted to be comparable to Scopus articles. Section III documents a large increase in citations to papers with all-Chinese addresses, and estimates China's share of global citations. Section IV examines the impact of China's new comparative advantage in science on its industrial structure and share of global production and trade in high-tech industries and economic innovation.

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[1]China had the largest number of science and engineering (S&E) bachelor and master degree graduates in the world, and the largest number of S&E PhDs granted to citizens from domestic universities and universities in other countries, particularly in the US. In 2016, over 5000 Chinese obtained S&E PhD degrees in the US (National Science Board, 2018, Table 26). China's research and development (R&D) expenditure in purchasing power parity units surpassed EU spending in 2015 and is expected to surpass US spending by 2020 (National Science Board, 2018, Tables 4 and 5), supporting the world's largest number of researchers. Available from: https://data.oecd.org/rd/researchers.htm (cited 8 August 2018).

[2]See https://en.wikipedia.org/wiki/One_Ring (cited 10 December 2018).

[3]We cover journal articles in those fields, excluding conference proceedings, books and book chapters because of their less frequent use of peer review. We exclude social sciences, economics and business as these often focus on issues specific to a country rather than basic science.

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II. China's Contribution to Scientific Publications

The standard measure of a country's contribution to the scientific literature credits it for papers with its address, and for a fraction of papers with its address and those of other countries. Measured by fractionated addresses in the Scopus database of international scientific journals, China's share of articles jumped from 4 percent of articles in 2000 to 18.6 percent in 2016, topping the US total.[4] While impressive, the share of addresses understates the Chinese contribution to scientific publication in two important ways.

First, it gives no credit to China for publications by Chinese researchers working at a non-Chinese address. This diaspora research community is large: approximately 17 percent of *non-Chinese addressed* articles in 2016 had at least one Chinese-named author.[5]

Second, it excludes articles in Chinese language journals outside the Scopus database. While articles in Chinese language journals gain fewer citations than articles in Scopus and thus likely make a smaller contribution to knowledge, the number of excluded Chinese language articles is so large that they cannot be ignored in any realistic assessment of China's contribution to global science. We develop a citation-based exchange rate to adjust these articles to "Scopus equivalence" and then measure China's share of the sum of Scopus articles and Scopus equivalent Chinese language articles.

We use the Scopus database to analyze China's position in scientific publications because Scopus indexes more journals and has wider coverage of countries and languages than the alternative Web of Science (WOS) database.[6] Scopus indexes far more Chinese journals than WOS: 556 journals published by Chinese publishers, 316 of which are Chinese language journals, and an additional 13 Chinese language journals outside China. WOS indexes 172 journals published in China, of which only 22 are Chinese language journals.

While Scopus includes far more China-published journals than WOS, it still leaves

[4]Measured in the Scopus database of scientific publications. Available from: https://www.scopus.com (cited December 2016 to October 2017). National Science Board (2018) Appendix Tables 5–27 show that China's share exceeded 17.8 percent for US addresses.

[5]Estimated from 20,000 randomly chosen articles in Scopus 2016, with persons from mainland or Chinese speaking areas differentiated from Chinese born elsewhere by first names (e.g. Wei is Chinese; James is not), as well as by surname.

[6]In 2017, Scopus listed 13,631 active S&E journals, 11,458 of which are English language journals compared to 8753 active journals indexed by WOS Science Citation Index Expanded (SCIE), of which 7280 are English language journals. Obtained from journal lists from the Scopus and WOS websites.

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out the vast majority of Chinese language scientific journals. To bring those publications into our analysis, we use data from China National Knowledge Infrastructure (CNKI), the most comprehensive database of scientific journals and other material published in China.[7] In 2017, the CNKI listed 4,216 science, engineering and math journals, the vast majority of which are in the Chinese language, and thus missing from Scopus.

We describe next how we credit China for researchers at non-Chinese addresses, and then describe how we combine the Scopus and CNKI publications for a global comparison.

1. Creating Address and Name-based Measures of National Contributions in Scopus

The standard measure of a country's contribution to scientific publications gives full credit for papers with its address and partial credit for cross-country collaborations proportionate to the country's share of all country addresses. It allots half credit to a country with half of the addresses on multi-country papers, a third to a country with one-third of addresses, etc.[8] Because splitting credit proportionate to the number of addresses rather than to the number of authors potentially understates the contribution of countries with many researchers, such as China, we modify the standard measure. We divide credit on a cross-country paper by the number of authors with a given country address relative to all authors. This adjustment modestly raises China's estimated contribution.

The greatest weakness of the standard address metric is that it gives *no* credit to a country for the publications of its researchers located at addresses outside the country. It counts a paper with, say, five Chinese authors working in the US as a US paper, just as it would a paper with five native-born Americans working in the US. Instead of crediting a country for a paper solely by address, we divide credit between addresses and authors' national background, identified in the publication data by the authors' names. Letting A be the number of authors with a given country address and N the number of authors' names associated with a country, we measure country c's

[7]We examine articles in the CNKI's China Academic Journals Database. The vast majority are Chinese language journals, with a few in English and other languages. For a short history of CNKI, see https://en.wikipedia.org/wiki/CNKI. *Global Academic Journal Impact Index 2018* by CNKI presents a detailed analysis of CNKI from the point of view of publishing science journals in China.

[8]"Articles are classified by their year of publication and are assigned to a region, country or economy on the basis of the institutional address(es) listed in the article. Articles are credited on a fractional-count basis. The sum of the regions, countries or economies may not add to the world total because of rounding." See note in Appendix Tables 5 – 27, Science and Engineering Indicators 2018.

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contribution to a paper as:

$$\alpha(A_c/A) + (1 - \alpha)(N_c/N), \quad (1)$$

where c subscripts denote address or national background/names and α is the weight given to addresses versus names. It varies from 1 (only addresses matter) to 0 (only names matter).

Equation (1) divides the contribution of authors whose name indicates that they are from a country other than the country of their address between the two countries. Ideally, α should reflect the relative contribution of people versus location on a paper. A paper based on research at a unique facility, say the CERN Hadron Collider, would presumably merit higher weight on the address dimension than a paper by theorists collaborating over the internet. On the other hand, a paper in country A with a visiting scientist from B using a technique developed in B deserves a higher weight on the name dimension. Another potential way to divide credit would be through funding sources. Research by Chinese scientists in the US funded by Chinese sources should be credited more to China than similar work funded by US sources. Lacking in-depth research on α for different papers, we weight addresses and names equally and examine how different weightings impact our findings.

Table 1 shows how our procedure distributes credit on a six-author paper with three non-Chinese named authors at non-Chinese addresses and three Chinese named authors, with 0–3 having non-Chinese addresses. It gives half credit for each Chinese named author with a non-China address to China on the basis of their name and half to the non-Chinese address. With six authors, each Chinese name at a non-Chinese address adds an additional 1/12th credit to China.

Table 1. Differences in Allocation of Credit for China

Number of Chinese names with non-Chinese address	Address based allocation of credit	Address and name based allocation of credit: 1/2 (China fraction of address) + 1/2 (China fraction of names)	Difference, Equation (1) – address-based
3	0	1/4 = 1/2 (0 +1/2)	3/12
2	1/6	1/3 = 1/2 (1/6 + 1/2)	2/12
1	2/6	5/12 = 1/2 (2/6 +1/2)	1/12
0	3/6	1/2 = 1/2 (1/2 + 1/2)	0

Source: Authors' calculations, as described in text.

Note: Example based on paper with six authors, three with non-Chinese names and addresses and three with Chinese names, by number of Chinese authors with non-Chinese addresses.

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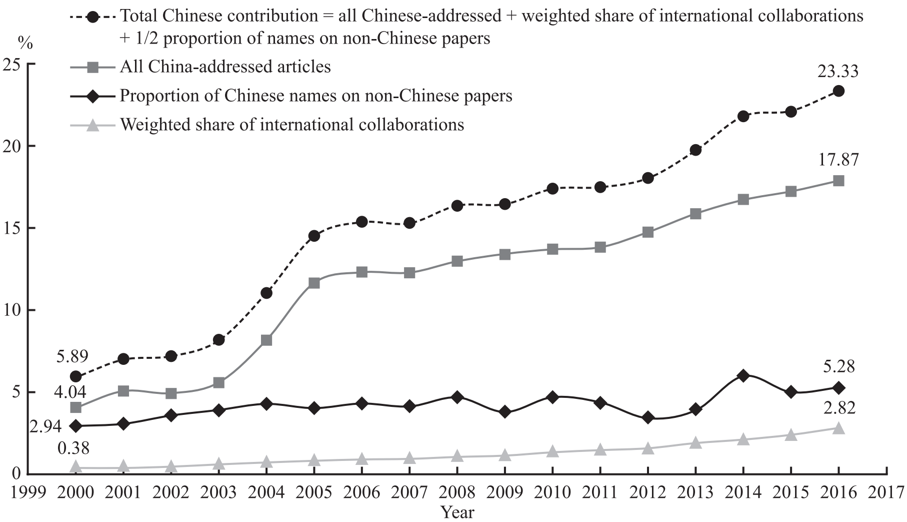
Following this procedure, we computed China's weighted fractional *contribution* to Scopus papers based on authors' address and name.[9] Because persons of Chinese ethnicity born outside the country are likely to have a Chinese last name but a first name from their country of birth, we use first and last names to determine likely Chinese birthplace/citizenship. Our measure counts Qing Yang as someone from China while counting David Yang as someone from outside China.[10] This measure limits mislabeling country of citizenship to naturalized citizens who kept their full Chinese name or to Chinese citizens publishing with their English first name.

Figure 1 displays our estimates. For 2016 we attribute 23.3 percent of the papers published in 2016 to China. This is 5.3 percentage points higher than the 18.0 percent of papers credited to China by the weighted address measure. To put this in perspective, 5.3 percent is comparable to the shares of Scopus papers of such scientific powers as Germany, Japan or the United Kingdom.

Figure 1. Weighted Share of International Journal Articles Credited to China, 2000–2016



Source: Scopus database.

Notes: Data classified by the year of publication, with papers weighted by proportion of Chinese addresses or names on the paper. Proportion of articles with non-Chinese addresses but at least one Chinese name estimated from a random sample of 20,000 Scopus articles with non-Chinese addresses in each year.

[9]We treat authors with multiple institutional addresses in different countries by dividing their contribution to addresses proportionately to the number of addresses by country. If one author on a two-author article listed one institution in country C and another in country D, we credit those countries with a quarter from that author.

[10]Freeman and Huang (2014) use Chinese surname to identify Chinese ethnicity of authors in US addressed papers. In cases where first names are unavailable, initials can also distinguish persons born in China from those born elsewhere. For instance, X, Q, Z, are common initials for Chinese first names but not for Western first names.

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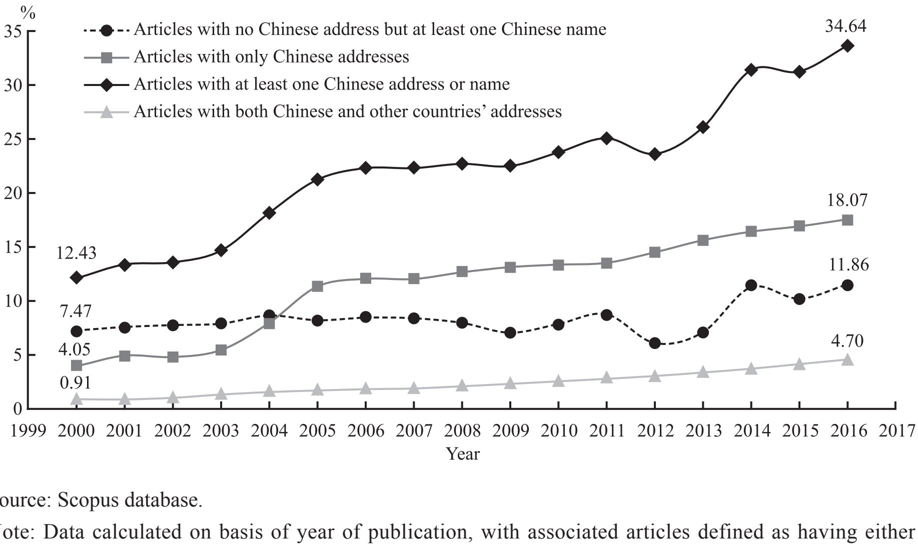
The figure differentiates papers into those with China-only addresses, those with Chinese and non-Chinese addresses, and those with Chinese-named authors but no Chinese address. The largest increase is in papers with all-Chinese addresses, which went from 4.0 percent of Scopus papers in 2000 to 17.9 percent in 2016.[11] International collaborations increased from 0.4 percent to 2.8 percent of papers while papers with Chinese names but no Chinese address rose from 2.9 to 5.3 percent. By our weighted measure, the Chinese proportion of Scopus papers increased nearly fourfold, from 5.9 percent in 2000 to 23.3 percent in 2016.[12] In absolute numbers, China added 3.3 million papers to the Scopus database: 2.2 million non-Chinese language papers and 1.1 million Chinese language papers.

Figure 2 shows China's contribution to the scientific literature in a different measure – the proportion of papers with *an association* to China. In the association metric, we count papers with at least one Chinese named author or address as being associated

Figure 2. Proportion of Scopus Articles Associated with China, 2000–2016



Source: Scopus database.

Note: Data calculated on basis of year of publication, with associated articles defined as having either a Chinese address or name.

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[11]The expanded Scopus coverage of Chinese language journals contributed, but the main factor was increased publications in non-Chinese language journals. The number of Chinese-addressed papers in a non-Chinese language journal increased by 539.2 percent from 2000 to 2016 compared to a 158.4 percent increase in Chinese language journals. In 2000, 39.1 percent of Chinese-addressed articles were in the Chinese language.

[12]Because China's share of both addresses and names increased substantially, China had a huge gain in its share of papers, regardless of the assumed α. Appendix Figure A shows that with $\alpha = 0$ (names get all the weight) China's share increased by 18.8 percentage points, while with $\alpha = 1.0$ (addresses get all the weight) its share increased by 16.0 points, bracketing the 17.4 point gain by our measure.

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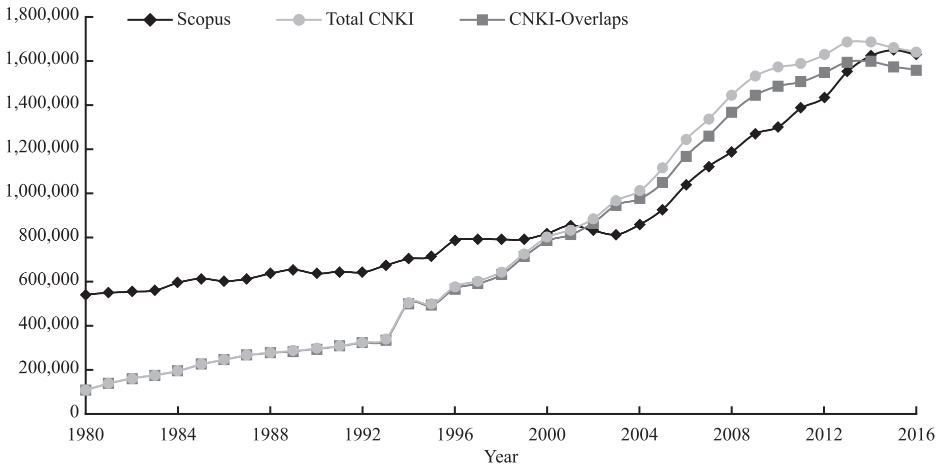
with the country. To the extent that Chinese authors connect with other Chinese researchers through an ethnic network, one author/address on a paper presumably suffices to spread results quickly to researchers in the group. In 2016, China was *associated* with 34.5 percent of papers published – a 22.1-point gain over its 12.4 percent association of papers published in 2000. The larger increase in association than in fraction-weighted names and addresses reflects growing research links between Chinese and other country researchers.

All told, Figures 1 and 2 show an increase in China's representation in international scientific journals at rates far above what seemed possible a decade or two earlier (May, 1997; Zhou and Leydesdorff, 2006; Kumar and Asheulova, 2011).

2. Missing Matter: Chinese Language Papers

The spread of English as the language of science has reduced the share of publications in other languages (Gordin, 2015); therefore, it is reasonable to expect that an increase in publications by Chinese researchers in English language Scopus journals would reduce the number of Chinese language publications. But Figure 3 shows no such pattern. The number of journal articles in the CNKI increased more or less coincident with the number of Scopus articles. In 2016, the number of Chinese articles outside of Scopus was a similar magnitude to all journal articles in Scopus –1.6 million.

Figure 3. Numbers of Science, Engineering, and Math Journal Articles in Scopus and CNKI, 1980–2016



Source: Scopus and China National Knowledge Infrastructure (CNKI) databases.

Notes: Data calculated for journal articles only. The modest number of articles in journals covered in both databases is shown by the difference between the Total CNKI and CNKI-Overlaps lines.

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How did China manage to increase the number of publications in Scopus and CNKI journals over the same period? The reason was the massive expansion of research activity. From 2000 to 2014, the number of faculties increased nearly 2.5-fold while the number of researchers quadrupled,[13] creating a huge supply of persons for whom publishing research is necessary to their career.

There is some indication in the data that the increase in publication in English came at the expense of publication in Chinese language journals. Figure 4 shows the number of publications in the two languages among researchers at universities in different tiers. Researchers at the highest quality "985" universities published more English language papers and less papers in Chinese. But researchers in less prestigious universities published more English language papers while roughly maintaining the number of Chinese language publications. It is likely that the movement of top researchers' publications to international journals opened spaces in Chinese language journals for academics in lower tier institutions. It is also likely that some scientists double-dipped in publishing, addressing the global research community in English and Chinese practitioners or policymakers, as well as researchers, in Chinese papers. We anticipate that PhDs and postdocs trained overseas publish more in English language journals while those trained in China publish more in Chinese journals. The increased number of domestic and foreign trained researchers was evidently sufficient to sustain the upward trend in publications in both languages.

We also compared Chinese and English language publications in 12 narrowly defined fields.[14] As Appendix Figure B shows, there was an upward trend in the number of English papers in all fields while the trend in Chinese language papers varied, declining in math, optics, metallurgy and instrumentation, which suggests substitution of English for Chinese; holding steady in microbiology; and increasing in seven fields, including oncology and pediatrics, where papers may target doctors in China as a key audience.

If the scientific content/impact of Chinese language papers was comparable to that of English language papers, the sum of Chinese articles in CNKI journals and our estimate of Chinese name and address weighted number of articles in Scopus, divided by the sum of all Scopus and all CNKI articles minus articles in overlap journals would

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[13]NBS (2001–2015) Tables 18, 20–22 show a 146.2 percent increase in the number of faculties from 2000 to 2014 and a 302.5 percent increase in the number of researchers.

[14]Because definitions of fields in the Chinese language journals are closer to those in the WOS database of international journals than to field definitions in Scopus, the Appendix figures compare the Chinese language papers with numbers of papers from the WOS rather than from Scopus.

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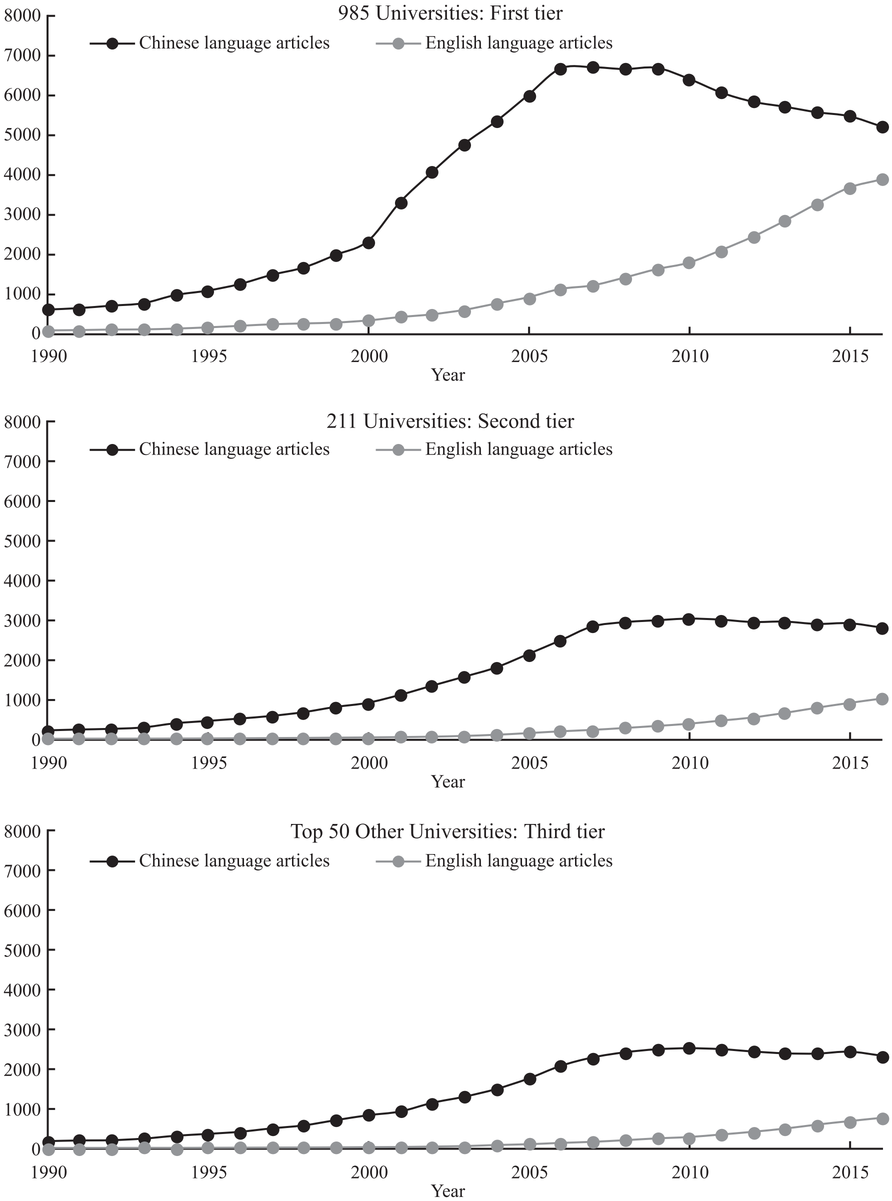
Figure 4. Average Number of Chinese and English Language Articles Published in Three Tiers of Chinese Universities, 1990–2016



Sources: Scopus and China National Knowledge Infrastructure (CNKI).

measure China's share of scientific publications. Given that almost all researchers in Chinese language journals are Chinese, the rough equality in the number of CNKI and

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Scopus articles in 2016 would then attribute 62 percent of scientific journal articles in that year to China![15]

But articles in the two databases are not comparable. CNKI journal articles are shorter and have fewer references than Scopus articles and thus presumably encapsulate less knowledge.[16] China's requirement that PhD and master degree candidates publish their thesis work to obtain a degree leads to the publication of many narrowly focused articles. Indicative of the quality difference, 44.6 percent of CNKI papers published in 2013 received no citations through 2016 compared to 29.0 percent of Scopus papers.[17] Fewer scientists read Chinese than English, giving Chinese publications less scientific impact. Recognizing the higher impact/quality of English language publications, Chinese universities offer incentives for publishing in those journals (Arbritis and McCook, 2017; Quan et al., 2017), which induces many researchers to send their best work overseas, adding to the quality disparity.

To provide a more realistic measure of China's contribution to global science that includes the missing Chinese language papers requires an equivalence scale or "exchange rate" between those papers and Scopus papers reflecting their relative importance. Taking citations as the most accessible and widely used indicator of impact or quality,[18] we transformed the number of missing Chinese papers into *Scopus equivalence papers* via a two-step procedure.

First, we calculated an exchange rate from the citations that Scopus and CNKI articles obtained in their own database. In 2013, a Scopus journal article averaged 9.2 citations from Scopus articles over the succeeding three years while a CNKI journal article averaged 2.3 forward citations from CNKI articles. This suggests a citation-based CNKI to Scopus exchange rate of approximately 0.25 (= 2.3/9.2).

But because neither database includes citations received from publications indexed in the other, this computation is incomplete. If (as turns out to be the case) CNKI articles

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[15]Crediting all CNKI articles to China, this is the sum of the 1/2 of articles in CNKI plus approximate 1/4th of the 1/2 from Scopus. Based on a random sample of 10,000 CNKI Chinese language articles in 2016, all had at least one China address and 9957 articles had only Chinese names.

[16]We randomly selected 2000 CNKI journal articles and found nine references per article compared to 42 references per article in Scopus. To the extent that articles with fewer references rely on less information and cover less material than articles with more references, a CNKI article has less scientific value than a Scopus article. At a ratio of 9:42 of references, a CNKI article would be approximately one-fifth as informative as a Scopus article.

[17]These estimates are based on all journal articles in Scopus and CNKI from August to November 2017.

[18]Citations are an imperfect measure of the scientific quality of an article. Some articles are cited because they are in a field with many researchers and a norm of citing papers. Some are cited because they appear in a prestigious journal or are written by a famous name (Merton, 1968). And some are neglected for long periods of time because they are "ahead" of their time (Ke et al., 2015).

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cite Scopus articles more than Scopus articles cite CNKI articles, the 0.25 estimate overvalues CNKI articles. To correct for the omission of cross-database citations, we sampled articles in each database in 2014, 2015 and 2016, downloaded their references and counted the number of references to 2013 publications in the other database. Recognizing that a reference from X to Y is the forward citation that Y gets from X, we used the reference data to estimate the number of citations a 2013 Scopus article received from CNKI articles through 2016 and the citations a 2013 CNKI journal article received from Scopus through 2016.

Table 2 presents the results of this analysis from random samples of articles in the two databases, as described in the table note. Consistent with the notion that Scopus articles carry a higher impact than CNKI articles, we estimate that 2013 Scopus articles received 3,276,350 citations from CNKI articles through 2016 whereas 2013 CNKI articles received l32,196 citations from non-Chinese language Scopus articles over the same period. Adding these citations to the number of citations in Scopus and CNKI reduces the exchange rate of a CNKI journal article from 0.25 to 0.20 of a Scopus paper.

Table 2. Estimated Citations to Scopus and CNKI Journal Articles, Including Cross-database Citations

Database	Number of total citations	Average citation per article
Total Scopus	17,533,029	11.31
Scopus to Scopus	14,256,679	9.19
CNKI only Chinese articles to Scopus non-Chinese articles	3,276,350	—
Total CNKI	3,831,190	2.28
CNKI to CNKI	3,798,994	2.26
Scopus non-Chinese articles to CNKI only Chinese articles	32,196	—

Source: Scopus and China National Knowledge Infrastructure (CNKI) databases, tabulated by authors, as described in the text.

We estimated the number of references that Scopus non-Chinese language articles give to Chinese language journals in CNKI (but not in Scopus) in 2013 by random sampling 10,000 articles from 2013 to 2017 (2000 per year) and counted the number of journal articles that referenced articles published in 2013. We found 19,859 journal references, nearly all (19,731) to Scopus journals and 64 to Scopus Chinese journals. We selected references with a journal title from the remaining references and matched journal titles with CNKI journals and found 58 references.

We estimated the number of references from CNKI Chinese language articles to

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Scopus non-Chinese language articles in 2013 by randomly sampling 500 articles from 2013 to 2017 (100 yearly) and found references to 2984 documents: 1031 Chinese language and 1848 non-Chinese language journal articles. Of these, 533 had the mark "[J]" that CNKI uses to identify journals. But we also identified a further 534 references to journal articles, giving us a total of 1067 references to non-Chinese journals. Thus we estimate that 50.87 percent (= 1067/(1067 + 1031)) of CNKI references were to non-Chinese journals and nearly all were in Scopus. A similar analysis of Chinese language papers in Scopus journals produced an estimate of 49.7 percent of journal citations to non-Chinese Scopus articles. The weighted Chinese address/authors' contribution to the 1067 CNKI references was 37.84 percent – nearly double China's 19.46 percent share of total citations, reflecting homophily in references.

The imbalance in citation rates explains our taking a larger sample of Scopus articles than of CNKI articles to obtain estimated cross-database citations. Because there were so few citations from Scopus to CNKI journals we needed a larger Scopus sample to obtain a reasonably accurate estimate of those citations.

Finally, counting 2016 CNKI publications at a Scopus equivalence of 0.20, we added the number of CNKI Scopus equivalent articles to the name and address weighted number of Scopus articles from China and divided this number by the sum of all Scopus articles and the number of Scopus equivalent articles from the missing Chinese journals to obtain a new estimate of China's share of scientific articles of 35.9 percent[19] – twice the 18.0 percent based on addresses on papers in Scopus.[20]

III. China's Contribution to Citations of Scientific Publications

"Numbers of papers exaggerate China's contribution to science. China has lots of copycat research but not enough innovative first-rate work. Lots of quantity but weak on quality."[21]

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[19]With approximately the same number of articles in Scopus and CNKI, the estimated 23.3 percent weighted share of Chinese papers in Figure 2 would become (0.23 + 0.20)/(1.00 + 0.20) = 0.358, adjusted for the Scopus equivalent articles, which is nearly identical to 35.9 percent from the exact figures.

[20]While Scopus includes 1844 non-Chinese non-English language journals out of 13,631 total journals reported in the Scopus Journal list for June 2017, it also leaves out many of those journals as well, which biases our estimated number of world Scopus equivalent articles downward, and assuming that Chinese researchers contributed little to the missing non-Chinese literature, biases our estimate of China's share of the true global total upward. But the Chinese language scientific literature is so much larger than other-language scientific literature that adjusting for missing journals in other languages would only modestly reduce our estimated China share of global science publications.

[21]Comment made by a skeptical seminar participant.

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In the 1990s when Chinese-addressed papers obtained around half the global average of citations per paper,[22] skepticism about quality was legitimate. But as the number of Chinese publications increased in 2000–2016, the number of citations to Chinese-addressed papers also substantially increased. This section shows that the increased number of papers and of citations per paper raised China's share of global citations from a negligible level to 37 percent of citations to Scopus equivalent papers, and provides evidence that at least part of the increase in citations is the result of improved Chinese science.

1. Citations in Scopus

To examine the change in the number of citations to Scopus articles written by Chinese researchers, we compare the average number of citations per paper by Chinese researchers relative to the global average of citations per paper for articles published in 2013 with average citations for articles published in 2000. The window for citations for 2013 publications is just three years, while the window for citations for 2000 papers is 15 years. As long as Chinese papers have a similar citation life cycle as other papers, the change in relative citations will measure the trend reasonably well. We estimate citations to papers with all Chinese addresses to those with Chinese and non-Chinese addresses, and to papers with Chinese-named researchers at non-Chinese addresses, and then for the average of the three groups, weighted by their proportion in the two years.

The upper panel of Figure 5 shows substantial change in the relative number of citations per paper. In 2000, papers with all-Chinese addresses received just 29 percent of the global average of citations per paper.[23] Papers with Chinese and other country addresses received 5 percent above the global average number of citations, while papers by Chinese researchers working outside of China had the most citations – 88 percent above the global average. The latter two groups made up a sufficiently large proportion of Chinese papers that China reached approximately the global average of citations. In 2013, the relative citations show a different picture. Citations to papers with all-Chinese addresses increased to 70 percent of the global

[22]National Science Board (2018) Appendix Tables 5–50. Figures for China: 1996, 0.46; 1997, 0.49; 1998, 0.48; 1999, 0.52; and 2000, 0.54. By contrast, US addressed papers averaged 1.42 times the global average, varying from 1.41 to 1.48 of the global average.

[23]This number is lower than the number of citations relative to the world average in the National Science Board (2018) statistics just examined because our number refers to all Chinese-addressed papers while their statistic relates to the fractionated share and includes international collaborations. In addition, our statistic excludes social science and is limited to journal articles while their statistic includes social science, book chapters and conference proceedings.

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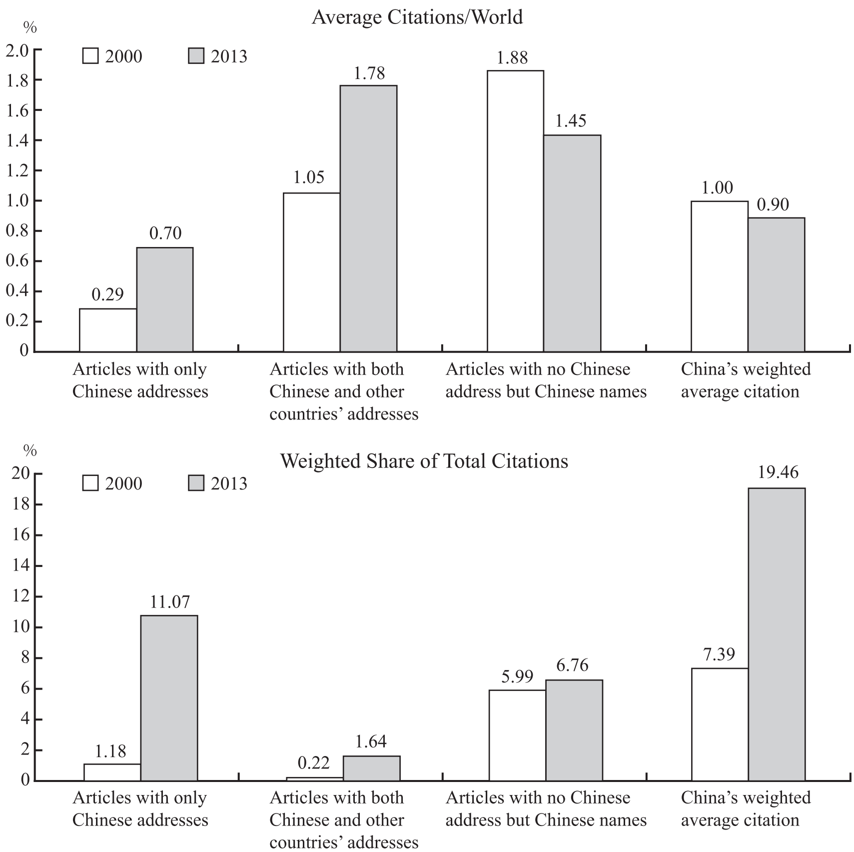
average. Citations to international collaborative papers increased to 78 percent above the global average in 2013. By contrast, citations of papers by Chinese researchers at non-Chinese addresses fell to 45 percent above the global average and were no longer the highest cited group. The citation per paper of our weighted average of the three groups fell to 10 percent below the world average because of the huge increase in the China-only share of papers.

Figure 5. Average Citations of Chinese Papers Relative to World and China's Share of World Citations, 2000 and 2013



Source: Scopus database.

Notes: Citations calculated from the same year and all following years relative to the world average, from the starting year to October 2017. Thus, citations for 2000 are based on more years than citations for 2013 articles. The upper panel shows average citations to different groups of Chinese papers relative to world average citation, as specified. The lower panel shows the ratio of all citations to Chinese papers, weighted by Chinese share of authors or addresses relative to citations to all papers in the world in the relevant year.

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Because we expect that the rapid increase of China-only addressed publications will dominate the future citation performance of Chinese papers, we examined other relevant statistics on citations to that group. The National Science Board's 2016 Science and Engineering Indicators (Figure 5–32) reports the ratio of the share of every country's papers in the top 1 percent of cited papers relative to the country's share of all papers. A ratio of 1 implies that the country produced proportionately as many upper 1 percent cited papers as of all papers, while ratios greater than or less than 1 imply that its papers had above/below average citations, respectively. China's relative share rose sharply from 0.31 in 1996 to 0.81 in 2012. National Science Board 2018 Science and Engineering Indicators (Figure 5-30) show an increase in the relative share from 0.60 in 2004 to 1.01 in 2014, placing China at the global average in the latter year.[24] Comparable calculations by the Organization for Co-operation and Development (OECD) for the upper 10 percent of cited papers find that China's relative share increased from 0.42 in 2005 to 0.76 in 2016. As a result of this significant increase, China rose to second in the list of countries producing top cited articles, accounting for 14.1 percent of the top 10 percent compared to the US's 25.5 percent.[25]

The bottom panel of Figure 5 shows the net effect of the increase in papers and changes in citations per paper on China's share of citations. China-only addressed papers had the largest increase, with its share of all Scopus citations jumping nearly ten-fold, from 1.18 percent citations in papers published in 2000 to 11.07 percent of citations in papers published in 2013. This accounted for 82 percent of the 12.07 percentage point increase in China's share of Scopus citations between the two periods.

2. Accounting for the Increase in China Citations in Scopus

Why did citations to Chinese-addressed papers increase so significantly?

There are two likely factors at work: the rapid growth of Chinese authored papers, which should boost citations as a result of the tendency for researchers to cite papers of researchers like themselves, including those with the same national or ethnic background ("citation homophily"); and the improved scientific quality of Chinese papers relative to the scientific quality of the average paper in Scopus.[26] Estimating the magnitude of

[24]Leydesdorff et al. (2014) compared the percentages of papers in the top 1 percent and top 10 percent of cited papers while Bornmann et al. (2015) showed an increase in the citations to Brazil, Russia, India and China on highly cited papers and a strong China connection with US.

[25]OECD, Science, Technology and Innovation Scorecard 2017, Figure 1.11 and Figure 1.12. http://www.oecd.org/sti/oecd-science-technology-and-industry-scoreboard-20725345.htm (cited 10 December 2018).

[26]We examined whether the extent to which the increase in China's citations per paper relative to the world average rose because papers from developing countries including China with below average citations increased their share of the world total and found that this "arithmetic" factor had only a minor impact on the trend.

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citation homophily requires modeling both preferences of scientists and the size of their scientific network, which goes beyond the scope of this paper. But we can show that the quality of Chinese research has substantially increased and is thus a major factor in the increase in citations of Chinese-addressed papers in two ways.

First, we examine the number of citations to Chinese-addressed papers from papers written by persons with little or no apparent connection to China. Assuming that the only plausible reason for non-Chinese papers to cite Chinese-addressed papers more frequently relative to others (adjusted for the rising share of Chinese-addressed papers) would be that the quality of the Chinese-addressed papers had increased, we used National Science Board Science and Engineering Indicators 2018 (Figures 5-27 and 5-28) that distinguish citations to papers with non-Chinese addresses from those with Chinese addresses from 1996 to 2014. We find that there was a 50 percent increase in the number of citations from "authors abroad" to Chinese-addressed papers relative to the world average.[27]

Second, we compute the presence of Chinese addresses or names in papers published in *Science* and *Nature*, two of the most prestigious journals in science. These journals have set high bars for publication; therefore, the only way for the share of Chinese papers published in *Science* or *Nature* to increase over time would be for the quality of those papers to improve relative to non-Chinese submissions. Appendix Figure C shows that the Chinese-addressed proportion of papers increased in both journals between 2000 and 2016, although it was still below China's share of fractionated addresses.[28] The proportion of Chinese names on papers with non-Chinese addresses, which were relatively high in 2000, more than doubled through 2016. To the extent that *Nature* and *Science* publish the best research, the best research conducted by Chinese scientists continues to come from outside the country.

3. Adding Citations from CNKI Journals

Because scientific publication databases count citations only from publications in their database, the analysis in Figure 5 is limited to citations to articles in journals indexed in Scopus. It does not count citations to articles in Chinese language journals outside the Scopus database, much less to cross-citations between CNKI and Scopus articles. To

[27]This increase is smaller than the increase in citations from Chinese-addressed papers, which is affected by both the presumed improved quality of papers and homophily. Xie and Freeman (2019) present a more detailed analysis of the relative importance of quality and homophily in the upward trend in citations to Chinese papers.

[28]Wang (2016) reported improved quality of Chinese-addressed publications based on their impact factor in Scopus while Basu et al. (2018) argued that China leads in some but not all scientific areas.

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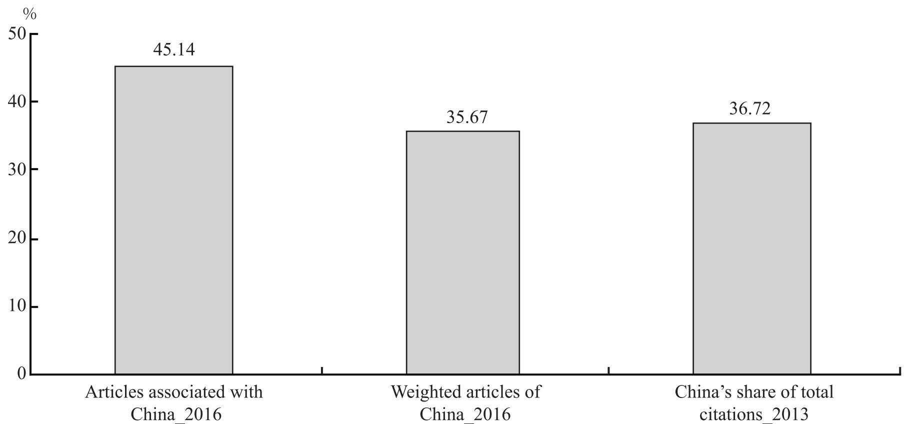
correct for the first omission, we added citations to articles in CNKI journals from the CNKI database. To correct for the second, we used our sample of articles from Scopus and CNKI journals described in Table 2 to estimate the number of citations across databases through their references. Adding the citations missing from Scopus to the number of citations in Scopus, we estimated the total number of citations in the world and the number of such citations attributable to China. Our estimate attributes 37 percent of three-year forward citations of 2013 scientific journal articles to Chinese research. This share is substantially greater than the Chinese share of Scopus citations because approximately half of the citations in the CNKI Chinese language journals are to articles in those journals and because a large proportion of their citations to Scopus articles are to articles by Chinese-addressed or Chinese-named researchers (Xie and Freeman, 2019).

Figure 6 summarizes the results of our analysis. Taking account of the contribution of Chinese researchers at non-Chinese addresses to papers in Scopus and the contribution of researchers publishing in Chinese language journals outside Scopus, we attribute 36 percent of Scopus equivalent articles and 37 percent of journal citations to China – roughly double the country's share of world population or world national production.[29] We further estimate that 45 percent of Scopus equivalent articles had some association with China.

Figure 6. China's Share of 2016 Global Science Publications and 2013 Global Citations



Source: Scopus and China National Knowledge Infrastructure (CNKI) databases. Authors' calculations as described in text.

[29]In 2017–2018 China had 18.2 percent of the world population and 18.3 percent of world GDP. See https://en.wikipedia.org/wiki/List_of_countries_and_dependencies_by population; https://en.wikipedia.org/wiki/List_of_countries_by_GDP_(PPP) (cited 10 December 2018).

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IV. Implications for China in the World Economy

Economists in the 1980s and 1990s used the "North–South" model of trade (Krugman, 1979) to explain why workers in advanced countries were more productive and earned more than similarly skilled workers in developing countries. The advanced country advantage lay in a monopoly of R&D-induced technological change and innovations augmented by the brain drain of skilled workers from developing to advanced countries in response to that advantage in knowledge. Northern (advanced) countries relative wages rose with the rate of technological change and fell as technology diffused to Southern (developing) countries. The possibility that low-income developing economies could compete in knowledge creation and innovation was unthinkable.

China's new comparative advantage in scientific knowledge undermines the premise of the North–South model and brain drain that low-income countries are necessarily disadvantaged in R&D and technological innovation. To the extent that increased production of scientific knowledge enables a country to move up the value-added chain in production and innovation, we would expect to see China's increased contribution to knowledge to be accompanied or followed by increases in its share of world output in "high-tech" industries and in innovation.

This section presents evidence of such increases in the period under study. While only detailed studies of the pathways from scientific knowledge to economic outcomes can "prove" that the increase in knowledge production caused or was necessary for economic change, China's advances in high-tech industrial production, patents and innovation are "smoking guns" that its investment in the production of scientific knowledge has indeed benefited its economy.

Table 3 shows the huge increase in China's share of global production and exports of goods and services in knowledge and technology intensive (KTI) industries, defined by the US National Science Foundation as high and medium high-tech manufacturing and commercial and non-commercial knowledge intensive services.

The speed at which China advanced in global production in new industries is extraordinary. In 2008–2009, the Obama Administration viewed green technologies as a way to restore US manufacturing jobs only to discover that China's share of solar photovoltaic cell production had increased from less than 1 percent in 2000–2001 to over 40 percent in 2010, while the US share fell from nearly 20 percent to 4–5 percent. By 2017, China was responsible for 60 percent of production of the world's photovoltaic cells as China surpassed other countries in deploying solar power.[30]

[30] https://en.wikipedia.org/wiki/Solar_power_in_China; https://en.wikipedia.org/wiki/Growth_of_photovoltaics#Deployment_by_country (cited 7 December 2018).

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Table 3. China's Shares of World Production and World Exports in KTI Industries, and the KTI Industry Share of China's GDP, 2001 and 2016

	China's share of world production		China's share of world exports		Share of Chinese production	
Year	2001	2016	2001	2016	2001	2016
High-tech industries	0.04	0.17	—	—	0.27	0.35
High-tech manufacturing (aerospace, communications and semiconductors, computers and office machinery, pharmaceuticals, and scientific instruments and measuring equipment)	0.06	0.24	0.1	0.24	0.03	0.03
Information communication technology (communications, computers, and semiconductors).	0.06	0.28	0.12	0.36	0.02	0.02
Medium high-tech manufacturing (motor vehicles, electrical machinery and apparatus, chemicals excluding pharmaceuticals, railroad and other transportation equipment, and machinery and equipment)	0.19	0.32	0.07	0.2	0.08	0.09
Knowledge intensive commercial services (business, financial, and information)	0.03	0.17	0.03	0.06	0.11	0.17
Knowledge intensive non-commercial services (education and health)	0.02	0.10	—	—	0.05	0.06

Source: Calculated from National Science Board, 2018; Appendix Tables, chapter 6.

Note: KTI, knowledge and technology intensive.

The last two columns of Table 3 show the within-country shift in Chinese GDP toward KTI industries. The shift in high and medium high-tech manufacturing is noticeably smaller than China's increased share of global production and of exports in those industries because of the shift in the Chinese economy toward services. In this case, greater weight is accorded to changes in high and medium manufacturing in the slower growing global economy than in the rapidly growing domestic economy. Note the opposite pattern for knowledge intensive services, which shows a substantial increase in the share of GDP but a less rapid increase in the share of global production because of the rapid expansion of such sectors in advanced countries.

The link from expertise in science and technology to the economy runs through innovation. In May 2014, US vice president Joe Biden dismissed China's ability to turn its S&E expertise into economic innovation. At an Air Force Academy commencement, Biden said that while China was graduating six to eight times as many scientists and engineers as the US, they were not innovating as Americans did: "I challenge you, name

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me one innovative project, one innovative change, one innovative product that has come out of China."[31]

To answer Biden's challenge, we looked at the locations of companies that made the "top ten innovations" at Las Vegas' World's Consumer Electronics Fair 2018. Four of the 10 were from China: an underwater drone (Beijing), a light electrical bicycle (Shenzhen), a fingerprint sensor for smart phones (Dongguan) and a virtual reality headset (Lenova).[32] The proportion of top innovations attributable to China almost surely varies across sectors, technologies and the particulars of selecting the top. Evidence from patent statistics, relative-standing in innovation indicators, and responses of international-business leaders regarding China's position in global innovation shows at the minimum that Consumer Electronics Fair data is not a random aberration. The Chinese economy is responding to the comparative advantage in knowledge with innovative business products.[33]

In sum, China's new comparative advantage in knowledge creation appears to be fueling its economic progress in knowledge and technology intensive industries and in innovation as well. While the link between the country's new advantage in the production of scientific knowledge and making products on the technological frontier is indirect, it is difficult to imagine a country moving rapidly and successfully in cutting edge sectors without a strong scientific base. Given that scientists and engineers are attracted to hot spots where knowledge is created, China's increased production of knowledge makes working in China more attractive not only to Chinese-born talents educated and/or working overseas but

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[31] http://politicalticker.blogs.cnn.com/2014/05/28/biden-name-one-innovative-product-from-china/ (cited 10 December 2018).

[32] https://touch4it.com/blog/ces-2018-novinky (cited 10 December 2018).

[33] China became the top global patenting country in the 2010s, but its patents are not of the same standard as those in the EU, Japan, or the US. Still, the number of Chinese patents granted by the US Patent and Trademark Office has increased, making China the fourth foreign country in patenting in 2017 (https://www.bloomberg.com/news/articles/ 2018-01-09/china-enters-top-5-of-u-s-patent-recipients-for-the-first-time; cited 7 December 2018). The 2018 Global Innovation Index ranked China 17th, up from 39th in 2013, but it uses many indicators on a per person basis, with the 2018 leaders in innovation being Switzerland, the Netherlands and Sweden (https://www.globalinnovationindex.org/Home). KPMG's 2018 survey of technology industry leaders places China second to the US as the most promising market for technological breakthroughs (https://www.prnewswire.com/news-releases/tech-industry-leaders-globally-increasingly-see-us-as-tech-innovation-and-disruption-leader-kpmg-report-300620327.html; cited 7 December 2018). However, Forbes' list of the 100 most innovative companies only includes seven Chinese firms (https://www.forbes. com/innovative-companies/list/2/#tab:rank; cited 7 December 2018); and the Boston Consulting Group list of the 50 most innovative companies only includes three from China (https://www.bcg.com/publications/2018/most-innovative-companies-2018-innovation.aspx; cited 7 December 2018).

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to others as well, as evinced by Apple and Google's 2017 announcements that they would open research facilities in China.[34]

To the extent that knowledge is the key to long term economic progress and to human well-being more broadly – the equivalent of Tolkien's "one ring that rules them all" in the *Lord of the Rings*[35] – the way China deploys its scientific resources will be a key driver of the direction of scientific and technological progress and of the world economy in the foreseeable future. To paraphrase Horace Greeley's advice to Americans as the US expanded to California, "Go West, young man, and grow up with the country,"[36] science is going East and will grow up with China.

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[34]https://www.cultofmac.com/472159/apple-will-open-two-additional-rd-centers-china-year/http://fortune.com/2017/12/13/google-china-artificial-intelligence/ (cited 7 December 2018).

[35]https://en.wikipedia.org/wiki/One_Ring (cited 10 December 2018). Unlike the one ring in Tolkien, which produces evil outcomes and thus must be destroyed for the story to have a happy ending, the ring of knowledge gives us ways to improve health and well-being and may prove critical in the struggle against the dangers of climate change.

[36]https://www.encyclopedia.com/history/dictionaries-thesauruses-pictures-and-press-releases/go-west-young-man-go-west (cited 10 December 2018).

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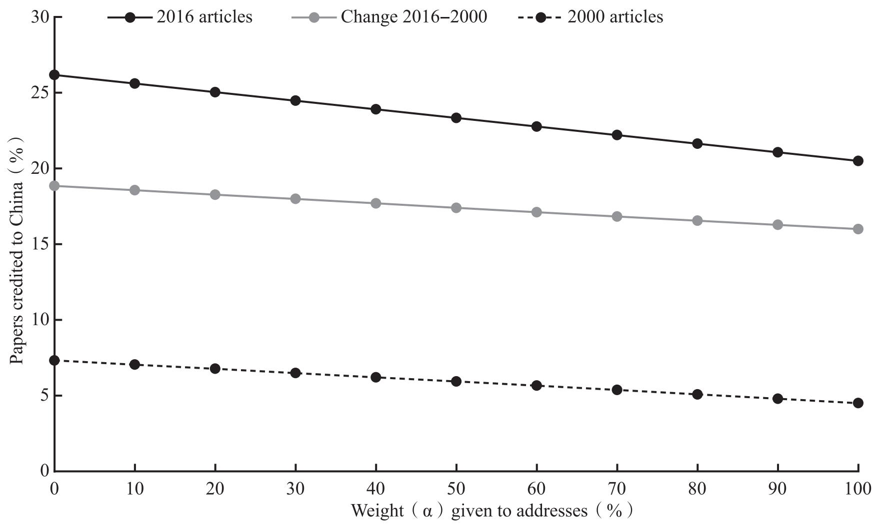
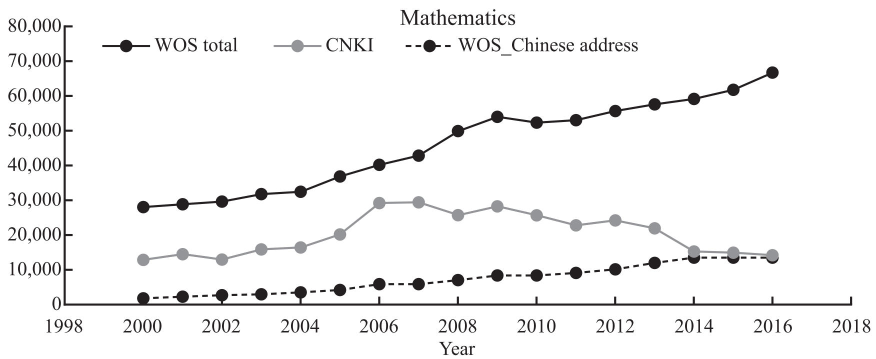
Appendix

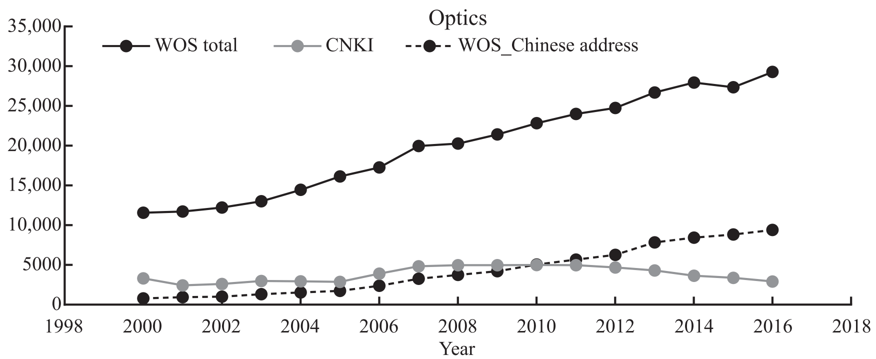
Figure A. Percentage of Scopus Papers Credited to China in 2000 and 2016 and Change in Percentage, Weighted by the Proportion of Credit Given to Address versus Names



Source: Calculated by authors, as described in Equation (1) in text.

Figure B. Number of Articles in 12 Fields in CNKI and WOS, 2000–2016





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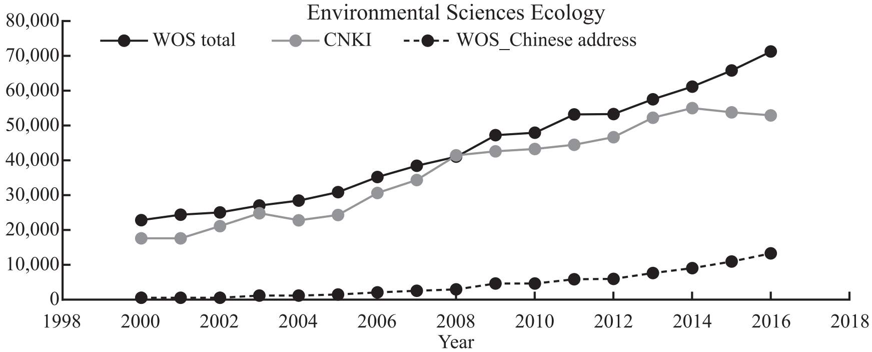

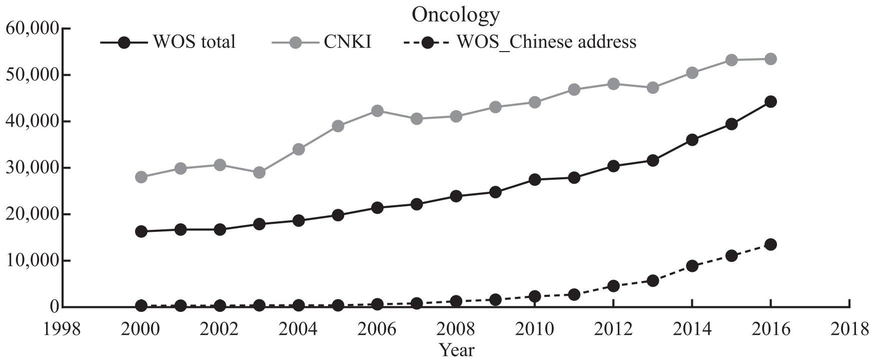

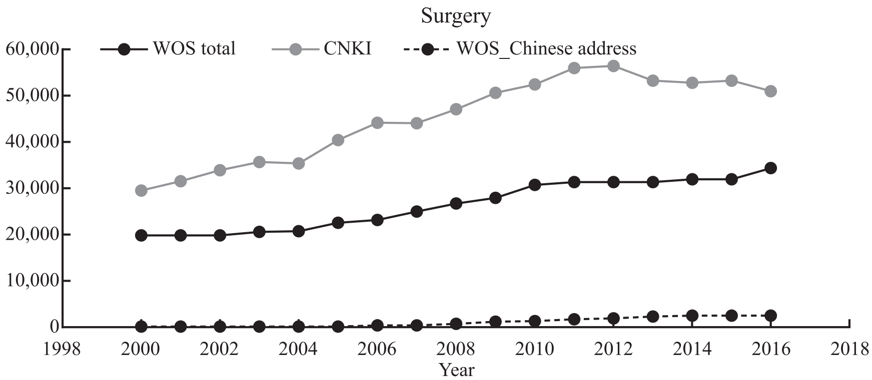

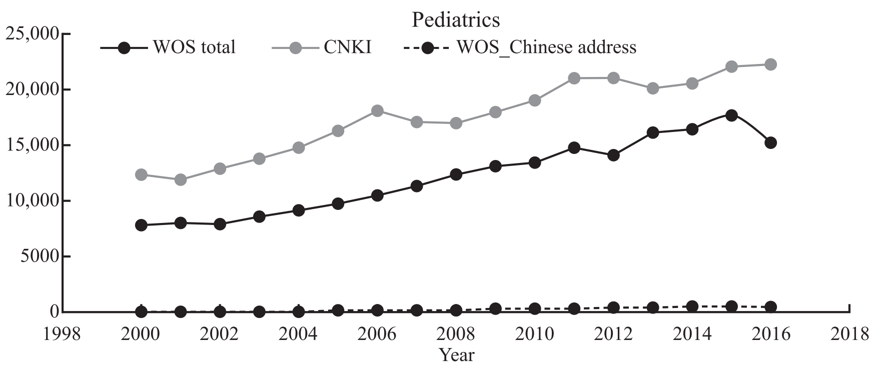

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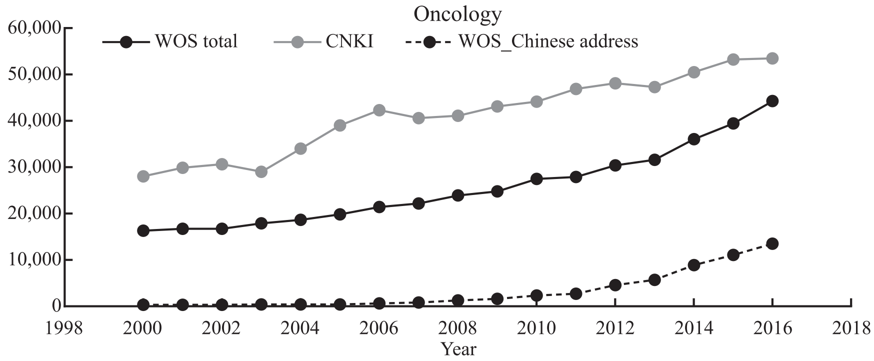

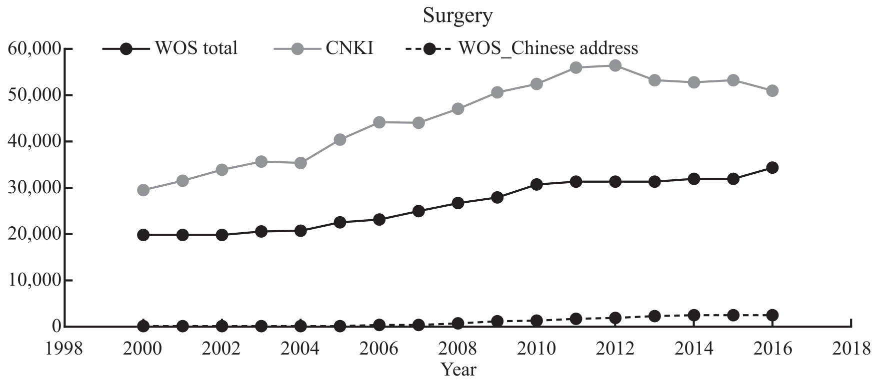

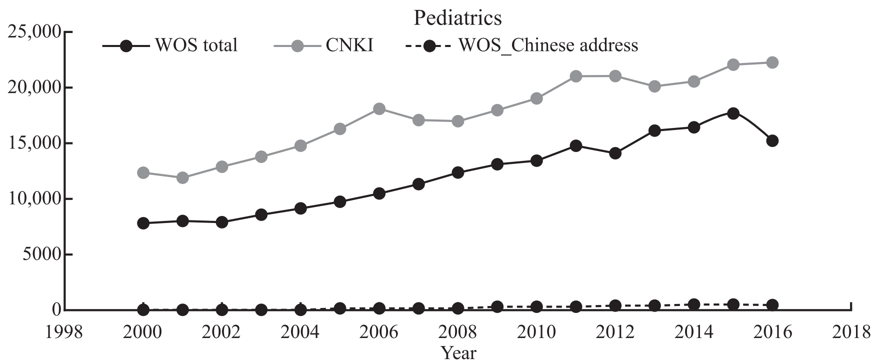

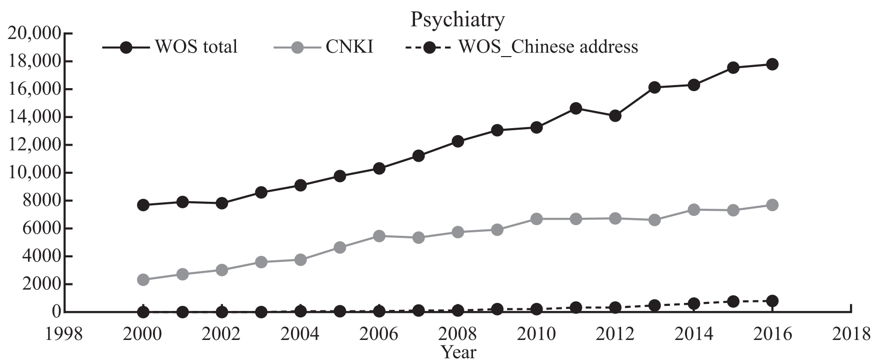

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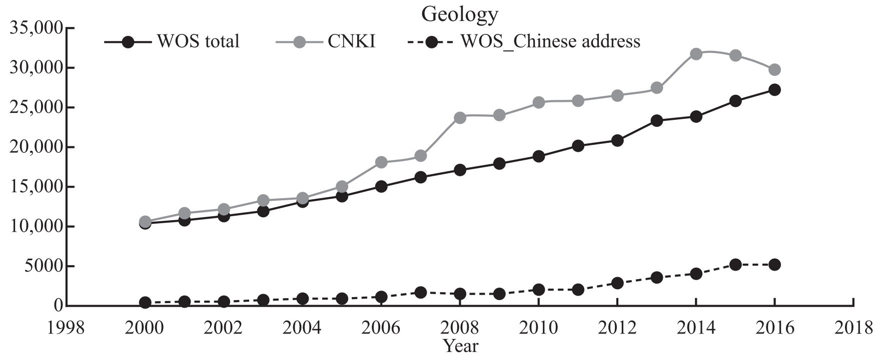
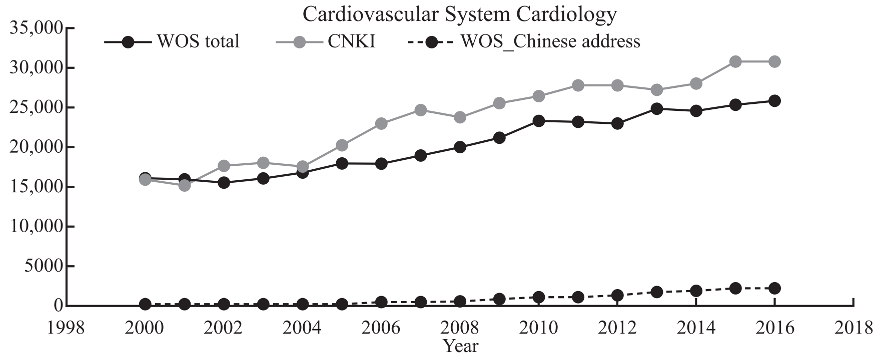
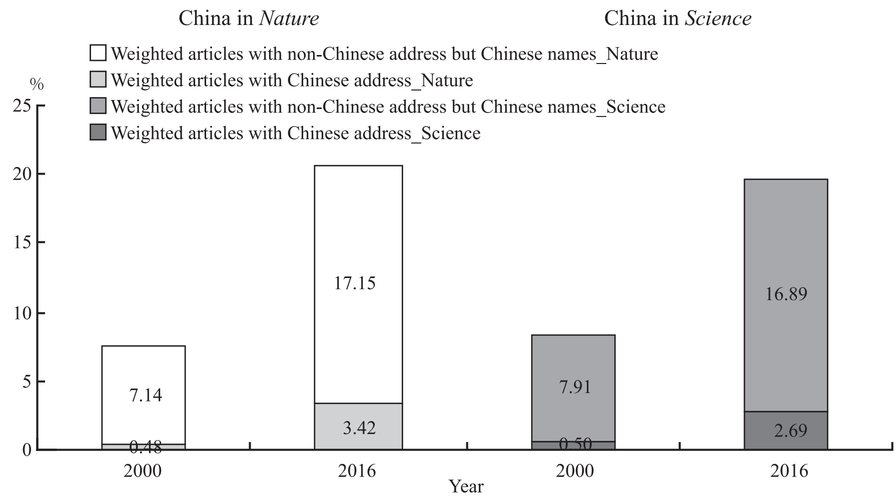




Sources: China National Knowledge Infrastructure (CNKI) and Web of Science (WOS).

Figure C. Fraction Weighted Share of Papers in *Nature* and *Science*, for Chinese Addresses and Names on Articles, 2000 and 2016



Sources: *Nature* and *Science*.

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