ORIGINAL ARTICLE

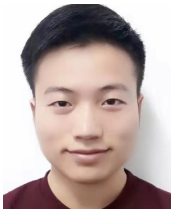
Association of Learned and Professional Society Publishers

(wileyonlinelibrary.com) doi: 10.1002/leap.1382 Received: 5 September 2020 | Accepted: 23 February 2021 | Published online in Wiley Online Library: 8 April 2021

# Evolution of scientific collaboration on COVID-19: A bibliometric analysis

Dezhong Duan [1]* and Qifan Xia [2]


D. Duan


Q. Xia

[1]School of Urban and Regional Sciences and Institute for Global Innovation and Development, East China Normal University, Shanghai, China

[2]School of Urban and Regional Sciences, East China Normal University, Shanghai, China

ORCID:
D. Duan: 0000-0001-9284-9666

*Corresponding author: Dezhong Duan, School of Urban and Regional Sciences and Institute for Global Innovation and Development, East China Normal University, 500 Dongchuan Rd, Minhang District, Shanghai 200241, China.
E-mail: dzduan@geo.ecnu.edu.cn

## Abstract

This paper considers the pattens of international collaboration by analysing publications on COVID-19 published in the first 6 months of the pandemic. The data set comprised articles on COVID-19 indexed in the Web of Science Core Collection (WoS CC) downloaded four times between 1 April 2020 and 1 June 2020. The analysis of 5,827 documents revealed that 128 countries, 23,127 authors, and 6,349 institutes published on the pandemic. The data reveal that the three main publishing countries were the USA, China, and England with Italy closely following. Although publication was widely spread, most of the institutions with the highest volume of output were in China. Network analysis showed growth in international cooperation with an average degree of country/region cooperation rising to 23.06 by 1 June. There was also a clear core-periphery structure to international collaboration. Institutional collaboration was shown to be highly regionalized. The data reveal a high and growing incidence of international collaboration on the pandemic.

**Keywords:** contributors, COVID-19, Scientific collaboration

## INTRODUCTION

Practice has long proved that international cooperation is not only the leading force in the global exploration of cutting-edge science but also the best way for the world to respond to issues such as resource and environment, climate change, health, and public safety (Adams, 2013; Adams & Loach, 2015; Choi *et al*., 2015; Freeman, 2010; Narin *et al*., 1991; Wagner *et al*., 2019). It took only 6 months from the discovery of the Novel Coronavirus (COVID-19) to more than 6 million confirmed cases and 300,000 deaths, which not only proves that the COVID-19 is too contagious to be overcome but also demonstrates the common destiny of all countries and regions in the era of globalization (Nature Editorial, 2020c; Washington, 2020). In fact, when this outbreak was declared as a Public Health Emergency of International Concern (PHEIC) on 30 January 2020 by the WHO, it was already indicated that international cooperation is the key to combating this pandemic (Berkley, 2020; Duan *et al*., 2020; Nature Editorial, 2020a, 2020b; Nature Medicine Editorial, 2020).

International scientific collaboration, an important part of international cooperation, has been given growing attention in innovation economics (Andersen, 2019; Bauder *et al*., 2018; Cassi *et al*., 2012, 2015; Gui *et al*., 2018a, 2018b; Wuestman *et al*., 2019), S&T policy (Chen *et al*., 2019; Fung & Wong, 2017; Gazni *et al*., 2012; Hou *et al*., 2008; Sun & Cao, 2020), and knowledge production and technology transfer (Aldridge & Audretsch, 2011; Ankrah & Al-Tabbaa, 2015; Bekkers & Freitas, 2008). Increasingly common and frequent knowledge flows crossing borders not only speed up the process of scientific

globalization but also constantly re-shape the global scientific landscape (Adams, 2013; Adams & Loach, 2015; Royal Society, 2011). International scientific collaboration is the key support of national competitiveness (Bathelt & Henn, 2014; Freeman, 2010). In the era of pandemic, cooperation in virus research is and important win-win for participating countries/regions. While improving the scientific research capacity, international cooperation also strengthens the capacity in pandemic prevention and control for each country and region (Nature Editorial, 2020c). In the past 5 months, researchers around the world have conducted a large number of in-depth studies on the structural morphology, gene sequence, pathogenic mechanism, diffusion mode, *etc*. of the COVID-19 virus, giving us a gradually clearer understanding of the virus and how to prevent and control the epidemic (Corey *et al*., 2020; Guan *et al*., 2020; Tian *et al*., 2020; Wu *et al*., 2020; Zhu *et al*., 2020). Within this are influential achievements jointly completed by researchers from multiple countries and institutions (Drew *et al*., 2020; Tian *et al*., 2020).

By exploring scientific collaboration among countries/regions and among institutes on COVID-19, this paper aims to answer the following two questions: (1) what is the structure of the international scientific collaboration network and the inter-institution collaboration network on COVID-19 research? (2) Who are the major contributing countries/regions and institutions participating in the scientific collaboration? The main contributions of this paper are twofold. Firstly, this paper seeks to enrich the literature on scientific collaboration through sorting out the relevant research about COVID-19. Specifically, it intends to test whether international scientific collaboration on COVID-19 is consistent with the existing findings on the structure of global scientific cooperation. It also tries to deepen our understanding of international collaboration in virus research.

**Key points**

- The US, China, England, and Italy published the most articles on COVID-19 in the first 6 months, with the US overtaking China by June 2020.
- International collaboration on articles about COVID-19 grew rapidly between April and June 2020.
- Institutional collaborations on COVID-19 articles tend to be localized indicating close research networks.
- Network analysis reveals a clear core-periphery structure of international collaboration on COVID-19 articles with growing participation of different countries.

## METHODOLOGY AND DATA

### Data

Although widely being criticized for its limitations (Cantner & Rake, 2014; Royal Society, 2011), co-publication is still one of the best ways to characterize scientific collaboration between authors, between countries/regions or between organizations (Basu & Kumar, 2000; Gui, Liu, & Du, 2019; Gui, Liu, Du, *et al*., 2019; He, 2009; Lemarchand, 2012; Liu & Gui, 2016; Sun & Cao, 2020; Sun & Grimes, 2016). The publications data analysed here was retrieved from Web of Science Core Collection (WoS CC), by adopting the full counting method (full credit to a country/institutes when at least one of the authors is from this country/institutes) to count the scientific collaborations among countries/regions or among institutes (Gauffriau & Larsen, 2005).

To clearly describe the development of scientific cooperation in the research of COVID-19, we counted all related publications (articles, reviews, letters and so on) collected on April 1, and collected new publications every half month thereafter. As of June 1, we had collected publications about COVID-19 at five points in time, which are April 1, April 15, May 1, May 15, and June 1. In addition, due to the difference in the initial naming of the new coronavirus, the publications search was sequentially retrieved through four topic words: novel coronavirus, SARS-CoV-2, 2019-nCoV, and COVID-19. All publications were published in 2020, and each search was conducted cumulatively, not discretely. The detailed description is as follows. On the Web of Science literature search page, we first selected WoS CC as the search database. Secondly, we selected the advanced search strategy, and use field identifiers and Boolean operators to create the search query, specifically, TS (topic) = novel coronavirus or TS = SARS-CoV-2 or TS = 2019-nCoV or TS=COVID-19. Thirdly, we selected the literature data published in 2020 in the search results. We repeated the above three-step search method at five points in time to obtain the accumulated data at each point of time. To understand the changes between every two points in time, by deleting the duplicated part of the data collected at the later point of time, we obtained the newly added data during every time period.

### Bibliometric tools

In this article, the bibliometric method is used to analyse the scientific cooperation on COVID-19. In the process, two kinds of software were used: VOSviewer and ArcGIS. VOSviewer is a software tool for constructing and visualizing bibliometric networks which can be constructed based on citation, bibliographic coupling, co-citation, or co-authorship relations (Perianes-Rodriguez *et al*., 2016; Van Eck *et al*., 2010; Van Eck & Waltman, 2010). ESRI's ArcGIS is a geographic information system for processing maps and geographic information. Its ArcMap product can be used to display and analyse the geographic structure of the cooperative network among authors, institutions, cities, and countries (Gui, Liu, & Du, 2019; Gui, Liu, Du, *et al*., 2019; Liu & Gui, 2016).

By integrating these two kinds of software, we analysed scientific cooperation around COVID-19 research both at national level and institute level. Specifically, we first used the VOSviewer to analyse the bibliographic data downloaded from WOS CC, drawing the scientific cooperation network among institutes or among countries/regions, obtaining the list of participating institutes or countries/regions, and the cooperation matrix between institutes or between countries/regions. Second, we used GPS Visualizer's Address Locator (www.gpsvisualizer.com/geocoder/) to geocode all participating institutes or countries/regions. Third, we imported the cooperation matrix with geographic information into ArcMap to analyse the geographical structure of scientific cooperation among institutes or among countries/regions.

## Network analysis

Network analysis is a powerful tool to reveal the structural characteristics of a scientific cooperation network (Gui, Liu, & Du, 2019; Gui, Liu, Du, *et al*., 2019). In this article, network analysis was applied to measure the structural characteristics of the scientific cooperation network on COVID-19. Specifically, the number of nodes and edges indicates the size of the network, that is, the number of countries/regions, institutes, or authors participating in cooperation. Density and average degree measure the cohesion of the network. The average clustering coefficient and the average path length are measures of the small world network (Watts & Strogatz, 1998). In addition, we also applied block modelling in network analysis to study the core-peripheral structure of the international cooperation network on COVID-19. The significant core-peripheral characteristics of the world economic system have been widely proven (Nemeth & Smith, 1985; Smith & White, 1992), and the core-peripheral structure of the global scientific cooperation network have also been discussed many times (Gui, Liu, & Du, 2019; Gui, Liu, Du, *et al*., 2019). We used the PAJEK program for block modelling (Waltman *et al*., 2010), which is a program for network analysis and visualization.

# RESULTS

## Descriptive analysis

We are interested in the distribution of publications by countries/regions, institutes and authors, and the leading contributing economies and institutes participating in scientific cooperation on COVID-19. Table 1 shows the descriptive statistics of the main indicators. During the 2-month observation from April 1 to June 1, the number of articles about COVID-19 published worldwide grew rapidly, from 808 as of April 1 to 5,827 as of June 1. The number of countries/regions and institutes participating in the research (sourced from author affiliations) also increased from 62 and 851 as of April 1 to 128 and 6,349 as of June 1, respectively. Cooperation is particularly evident in COVID-19 research. Most of the countries/regions, institutes and authors involved in the research have cooperated with others to some degree.

## The growth of COVID-19 studies

Despite the increasing number of countries/regions participating in the research, publications on COVID-19 were highly concentrated in a few countries/regions. China, the US, and England have consistently ranked among the top three in terms of

**TABLE 1** Descriptive statistic of publications and collaborations about COVID-19.

| | As of April 1 | April 2–15 | April 16–May 1 | May 2–15 | May 16–June 1 | As of June 1 |
|---|---|---|---|---|---|---|
| In terms of publication | | | | | | |
| Number of documents | 808 | 457 | 878 | 1,493 | 2,191 | 5,827 |
| Number of countries/regions | 62 | 68 | 66 | 93 | 103 | 128 |
| Number of institutes | 851 | 1,044 | 2,160 | 2,378 | 3,241 | 6,349 |
| Number of Authors | 3,029 | 2,787 | 4,021 | 6,433 | 9,736 | 23,127 |
| In terms of collaboration | | | | | | |
| Number of countries/regions participating in scientific collaboration | 60 | 62 | 57 | 83 | 96 | 122 |
| collaborations among countries/regions | 537 | 642 | 947 | 1,614 | 2,143 | 5,886 |
| Number of institutes participating in scientific collaboration | 801 | 950 | 1,760 | 2,190 | 2,960 | 5,879 |
| collaborations among institutes | 2,995 | 4,199 | 6,420 | 11,145 | 15,602 | 40,384 |
| Number of authors participating in scientific collaboration | 2,976 | 2,547 | 3,614 | 6,142 | 11,245 | 21,014 |
| collaborations among authors | 21,176 | 27,786 | 30,561 | 36,166 | 81,739 | 197,428 |

*Note:* The data in the table are de-duplicated. Institution data are matched by country and institution name, and author data is matched by institution and author name.

**TABLE 2** Number of documents published by main countries/regions at five points in time.

| Country/region | As of April 1 | As of April 15 | As of May 1 | As of May 15 | As of June 1 |
|---|---|---|---|---|---|
| US | 118 | 248 | 442 | 810 | 1,389 |
| China | 246 | 460 | 650 | 934 | 1,295 |
| England | 41 | 108 | 196 | 358 | 616 |
| Italy | 23 | 68 | 164 | 345 | 599 |
| Canada | 29 | 53 | 78 | 150 | 262 |
| India | 12 | 35 | 66 | 165 | 252 |
| Germany | 31 | 55 | 86 | 151 | 245 |
| Australia | 21 | 45 | 77 | 136 | 242 |
| France | 18 | 29 | 40 | 106 | 202 |
| Iran | 6 | 25 | 92 | 125 | 177 |
| Switzerland | 16 | 38 | 65 | 108 | 151 |
| Spain | 6 | 14 | 24 | 59 | 141 |
| Singapore | 12 | 39 | 47 | 83 | 139 |
| Brazil | 8 | 16 | 36 | 68 | 118 |
| Netherlands | 14 | 26 | 33 | 61 | 102 |
| Japan | 20 | 33 | 35 | 58 | 99 |
| South Korea | 27 | 42 | 61 | 75 | 97 |
| Turkey | 0 | 4 | 14 | 55 | 96 |
| Saudi Arabia | 26 | 32 | 41 | 45 | 68 |
| Chinese Taiwan | 11 | 14 | 21 | 43 | 51 |

cumulative publications. China was originally leading in terms of publication volume, indicating that China's leading research work laid a solid knowledge base for the world's knowledge of COVID-19. With the development of the pandemic, the US became prominent as a global scientific centre. As of June 1, the US had surpassed China in the number of publications, reaching 1,389. China ranks second with 1,295 publications, and England ranks third with 616 publications. In addition, Italy, Canada, India, Germany, Australia, and France also have published a large amount of literature on COVID-19 (Table 2).

Similarly, the publication pattern of COVID-19 at the institute-level also showed a high uneven degree of concentration (Table 3), that is, most institutes only published one document, and the number of institutes publishing more than 20 documents is only 86 as of June 1. Institutes from China have the highest volume of scholarly output on COVID-19 research. According to the literature statistics as of April 1, 17 of the top 20 institutes in terms of publications were from China. The CAS, HKU, and HUST ranked among the top three with 27, 21 and 18 publications, respectively. As of June 1, although the number of Chinese institutes in the top 20 decreased to 10, 4 of the top 5 came from China. HUST, WU, and HKU ranked first, second, and third with 143, 102, and 81 documents, respectively. Moreover, institutes from the US, England, Canada, Italy, Iran, Australia also played an important role in COVID-19 research.

More and more researchers also participated in COVID-19 research. The literature statistics as of April 1 showed that 3,029 researchers published studies of COVID-19 and related fields, and this increased to 23,127 by June 1. In addition, China's noticeable performance at the national and institutional level has not been confirmed at the individual level. In the literature statistics on April 1, only 6 of the top 20 authors were from China (and two authors also received partial support from Chinese institutions), while eight authors were from the HU in Japan. As of April 1, Shi Zhengli, a researcher from CAS published the largest number of articles in the world on COVID-19 research, reaching 8. As of June 1, 8 of the top 20 authors were from China, with 4 of them from Chinese Hong Kong. As of June 1, Wiwanitkit Viroj, a researcher from DDYPU and HMU had published the largest number of research articles in the world, reaching 26 publications (Table 4).

## Contributions to scientific cooperation

This section traces network evolution on scientific cooperation around COVID-19 articles and analyses the countries/regions,

**TABLE 3** Top 20 institutes with the most publications on COVID-19 at five points in time.

| As of April 1 | | As of April 15 | | As of May 1 | | As of May 15 | | As of June 1 | |
|---|---|---|---|---|---|---|---|---|---|
| Ins. | Articles | Ins. | Articles | Ins. | Articles | Ins. | Articles | Ins. | Articles |
| CAS | 27 | HUST | 38 | HUST | 63 | HUST | 101 | HUST | 143 |
| HKU | 21 | HKU | 38 | HKU | 44 | WU | 75 | WU | 102 |
| HUST | 18 | CAS | 35 | WU | 44 | HKU | 59 | HKU | 81 |
| FU | 15 | FU | 33 | CAS | 37 | ZJU | 54 | ZJU | 76 |
| CMU | 14 | WU | 28 | ZJU | 37 | FU | 50 | HMS | 71 |
| ZJU | 14 | ZJU | 25 | FU | 35 | CUHK | 47 | FU | 66 |
| WU | 13 | CMU | 21 | CMU | 34 | CMU | 44 | UT | 65 |
| CUHK | 11 | SYSU | 21 | UTMS | 32 | HMS | 44 | OU | 63 |
| GMU | 11 | CUHK | 20 | CAMS | 29 | OU | 44 | CUHK | 62 |
| SCAU | 11 | CAMS | 19 | SYSU | 27 | UTMS | 41 | UoM | 62 |
| SYSU | 11 | SJTU | 18 | SJTU | 26 | UT | 41 | CMU | 58 |
| UoS | 11 | SCU | 18 | OU | 26 | CAS | 40 | UCL | 58 |
| CAAS | 10 | LSHTM | 17 | UCL | 25 | CAMS | 39 | UTMS | 54 |
| HU | 10 | GMU | 16 | CUHK | 24 | SJTU | 39 | NUS | 53 |
| SJTU | 10 | PU | 16 | HMS | 24 | UCL | 36 | CAMS | 52 |
| SCU | 10 | TSU | 15 | PU | 22 | PU | 33 | CAS | 52 |
| CUMB | 9 | UoS | 15 | SCU | 22 | UoM | 32 | SJTU | 51 |
| HZAU | 9 | UCL | 14 | SBUMS | 21 | SCU | 31 | UMG | 51 |
| U. CAS | 9 | OU | 14 | LSHTM | 20 | SYSU | 31 | CU | 50 |
| CAMS | 8 | CQMU | 13 | ICU | 19 | CU | 30 | UMB | 47 |

Abbreviations: CAAS, Chinese Academy of Agricultural Science; CAMS, Chinese Academy of Medical Sciences; CAS, Chinese Academy of Sciences; CMU, Capital Medical University; CQMU, Chongqing Medical University; CU, Columbia University; CUHK, Chinese University of Hong Kong; CUMB, Charité-University Medicine Berlin; FU, Fudan University; GMU, Guangzhou Medical University; HKU, University of Hong Kong; HMS, Harvard Medical School; HU, Hokkaido University; HUST, Huazhong University of Science and Technology; HZAU, Huazhong Agricultural University; ICU, Imperial College London; LSHTM, London School of Hygiene & Tropical Medicine; NUS, National University of Singapore; OU, Oxford University; PU, Peking University; SBUMS, Shahid Beheshti University of Medical Sciences; SCAU, South China Agricultural University; SCU, Sichuan University; SJTU, Shanghai Jiao Tong University; SYSU, Sun Yat-Sen University; TSU, Tsinghua University; U. CAS, University of CAS; UCL, University College London; UMB, University of Melbourne; UMG, University of Michigan; UoM, University of Milan; UoS, University of Sydney; UT, University of Toronto; UTMS, Tehran University of Medical Sciences; WU, Wuhan University; ZJU, Zhejiang University.

and institutions contributing to the promotion of COVID-19 scientific cooperation.

## Cooperation network evolution

According to Table 5, the international cooperation network on COVID-19 is moving towards intensiveness, with the network density increasing from 0.163 as of April 1 to 0.191 as of June 1. The average degree also increases continuously from 9.633 to 23.06, which means that a country/region has cooperated with 23.06 other countries/regions on average. As of June 1, the density of international cooperation network was only 0.191, indicated that in the first few months of the outbreak, the international cooperation network was relatively sparse. This shows that although the number of countries/regions participating in the COVID-19 research is increasing, international cooperation is mainly found in a few countries/regions.

The density of inter-institute cooperation networks is generally lower than 0.009 with a continuous downward trend. While the average degree shows an upward trend, increasing from 6.804 as of April 1 to 12.308 as of June 1 (Table 5). Although it is said that the cooperation among countries/regions is undertaken by institutes, when the research scale is placed at the institute level, the global cooperation network on COVID-19 appears abnormal coefficient and cooperation becomes extremely precious. Besides, based on Watts and Strogatz's work (Watts & Strogatz, 1998) about small-world network's features, we also found that the scientific cooperation network on COVID-19 both

**TABLE 4** Top 20 authors with the most publications and their related information.

| As of April 1 | | | As of June 1 | | |
|---|---|---|---|---|---|
| **Author** | **Institute** | **Publications** | **Author** | **Institute** | **Publications** |
| Shi, Z. L. | CAS | 8 | Wiwanitkit V. | DDYPU and HMU | 26 |
| Holmes E. C. | FU and UoS | 7 | Lippi G. | VU | 17 |
| Drosten C. | CUMB | 7 | Joob B. | SMA | 15 |
| Akhmetzhanov A. R. | HU | 7 | Memis Z. A. | EMU and AU | 14 |
| Linton N. M. | HU | 7 | Drosten C. | CUMB | 12 |
| Nishiura H. | HU | 7 | Nishiura H. | HU | 12 |
| Memish Z. A. | EMU and AU | 7 | Cowling B. J. | HKU | 11 |
| Yuen K. Y. | HKU | 6 | Leung G. M. | HKU | 11 |
| Zhang W. | CAS | 6 | Rodriguez-Morales A. J. | ACI, UTP and FUAA | 11 |
| Hayashi K. | HU | 6 | Yang L. | HKPU | 11 |
| Jung S. M | HU | 6 | Yang Y. | ISMMS | 11 |
| Kinoshita R. | HU | 6 | Zhang W | CAS | 11 |
| Kobayashi T. | HU | 6 | He D. H. | HKPU | 10 |
| Xiao S. | HAU | 6 | Jiang S. B. | NYBC and FU | 10 |
| Yang Y. | HU | 6 | Li H. | CJFH and CAMSPUMC | 10 |
| Zumla A. | UCL | 6 | Zumla A. | UCL | 10 |
| Baric R. S. | UNC | 5 | Akhmetzhanov A R. | HU | 9 |
| Fang L. | HAU | 5 | Cao B. | CJFH, CAMSPUMC, TSU and CMU | 9 |
| Feng L. | CAAS | 5 | Li T. S. | CAMSPUMC | 9 |
| Jiang S. B. | NYBC and FU | 5 | Linton N. M. | HU | 9 |

Abbreviations: ACI, Asociación Colombiana de Infectología; AU, Alfaisal University; CAMSPUMC, Chinese Academy of Medical Sciences & Peking Union Medical College; CJFH, China-Japan Friendship Hospital; DDYPU, Dr. DY Patil University; EMU, Emory University; FUAA, National Autonomous University of Mexico; HKPU, Hong Kong Polytechnic University; HMU, Hainan Medical University; ISMMS, Icahn School of Medicine at Mount Sinai; NYBC, New York Blood Center; SMA, Sanitation 1 Medical Academy Centre; UTP, Technological University of Pereira; VU, Verona University.

at national-level and institute-level is a typically small-world network with higher clustering coefficients and shorter average path length compared with a random graph.

Meanwhile, the international cooperation network on COVID-19 has an obvious core-periphery structure (Fig. 1), which can be divided into four categories: core, strong semi-periphery, semi-periphery, and periphery (Nemeth & Smith, 1985; Smith & White, 1992; Wallerstein, 1974). The international cooperation network on COVID-19 as of April 1 was a remarkable double-core pyramid structure, only the US and China located in the core position. As of June 1, China moved down to the strong semi-periphery group, a single-core structure of the international cooperation network on COVID-19 led by the US has been taking shape. In the strong semi-periphery layer, from April 1 to June 1, except for the change in China, India rose from the semi-periphery to this level at May 1 but returned at June 1, Saudi Arabia fell to the semi-periphery at May 1 and remained its status at June 1. However, the number of countries or regions located in the strong semi-periphery is relatively stable. In the semi-periphery, the number of countries or regions increased significantly from 9 at April 1 to 40 at June 1. Surprisingly, countries with large numbers of publications were also located in this layer, such as Iran, Switzerland, Spain, Singapore, *etc*.

## The contributing countries/regions

Using the ArcMap platform, the international scientific cooperation on COVID-19 at three points in time, as shown in Fig. 2, is visualized geographically. The Changing geography of international cooperation on COVID-19 confirmed that COVID-19 research gradually developed from individual countries leading to global participation. The tri-polar landscape of global science dominated by North America, Asia-Pacific, and Europe has also been proven in COVID-19 research. Cooperation between countries generally occurs within or between these three regions, and

**TABLE 5** Topological characteristics of scientific cooperation network on COVID-19.

| Indicators | As of April 1 | As of April 15 | As of May 1 | As of May 15 | As of June 1 |
|---|---|---|---|---|---|
| International cooperation network | | | | | |
| Nodes | 60 | 77 | 96 | 112 | 122 |
| Edges | 289 | 487 | 777 | 1,055 | 1,407 |
| Density | 0.163 | 0.186 | 0.170 | 0.170 | 0.191 |
| Average degree | 9.633 | 12.649 | 16.188 | 18.839 | 23.06 |
| Average clustering coefficient | 0.752 | 0.749 | 0.775 | 0.769 | 0.766 |
| Average path length | 2.095 | 2.065 | 2.041 | 2.028 | 1.955 |
| Inter-institute cooperation network | | | | | |
| Nodes | 801 | 1,495 | 2,454 | 3,980 | 5,879 |
| Edges | 2,725 | 6,530 | 12,329 | 22,572 | 36,180 |
| Density | 0.009 | 0.006 | 0.004 | 0.003 | 0.002 |
| Average degree | 6.804 | 8.736 | 10.048 | 11.343 | 12.308 |
| Average clustering coefficient | 0.857 | 0.857 | 0.860 | 0.851 | 0.846 |
| Average path length | 4.094 | 3.816 | 3.849 | 3.761 | 3.694 |

the US, China, and England are the three key nodes (Tables 6 and 7).

In the early stage of the outbreak, China played a vital role in promoting international scientific cooperation. Literature statistics as of April 1 showed that China cooperated with 31 countries/regions 132 times. And among the top 20 partnerships, there are 9 pairs with China's participation, 4 of which are in the top 5. Meanwhile, the US and England also performed well in the international scientific cooperation of COVID-19, conducting 112 and 77 collaborations with 35 and 28 countries/regions respectively. In addition, the US also participated in 5 of the top 20 partnerships. As of May 1, the US cooperated with 70 countries/regions 476 times, surpassing China both in the number of partners and collaborations. While China conducted 353 collaborations with 52 countries/regions and England carried out 351 collaborations with 60 countries/regions. Of the top 20 partnerships, 8 pairs have US's participation, and China and England participated in 7 and 5 pairs respectively. By June 1, as the hub of COVID-19 global scientific cooperation, the United States was further consolidated. It has cooperated with 95 countries/regions 1,304 times, far more than other countries/regions both in the number of partners and collaborations. Among the top 20 partnerships, there were 8 pairs with US participation, 4 of which are in the top 5. England also surpassed China by conducting 972 collaborations with 84 countries/regions, while China cooperated with 72 countries/regions 776 times. And in the top 20 partnerships, both China and England participated in 6 of them.

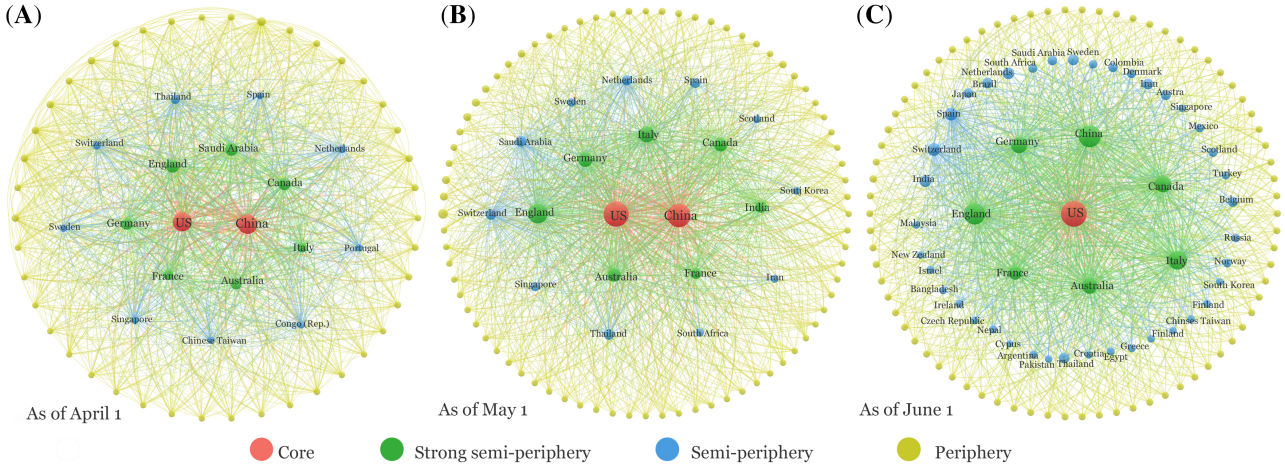



**FIGURE 1** The core-periphery structure of international cooperation network on COVID-19 at three points in time.

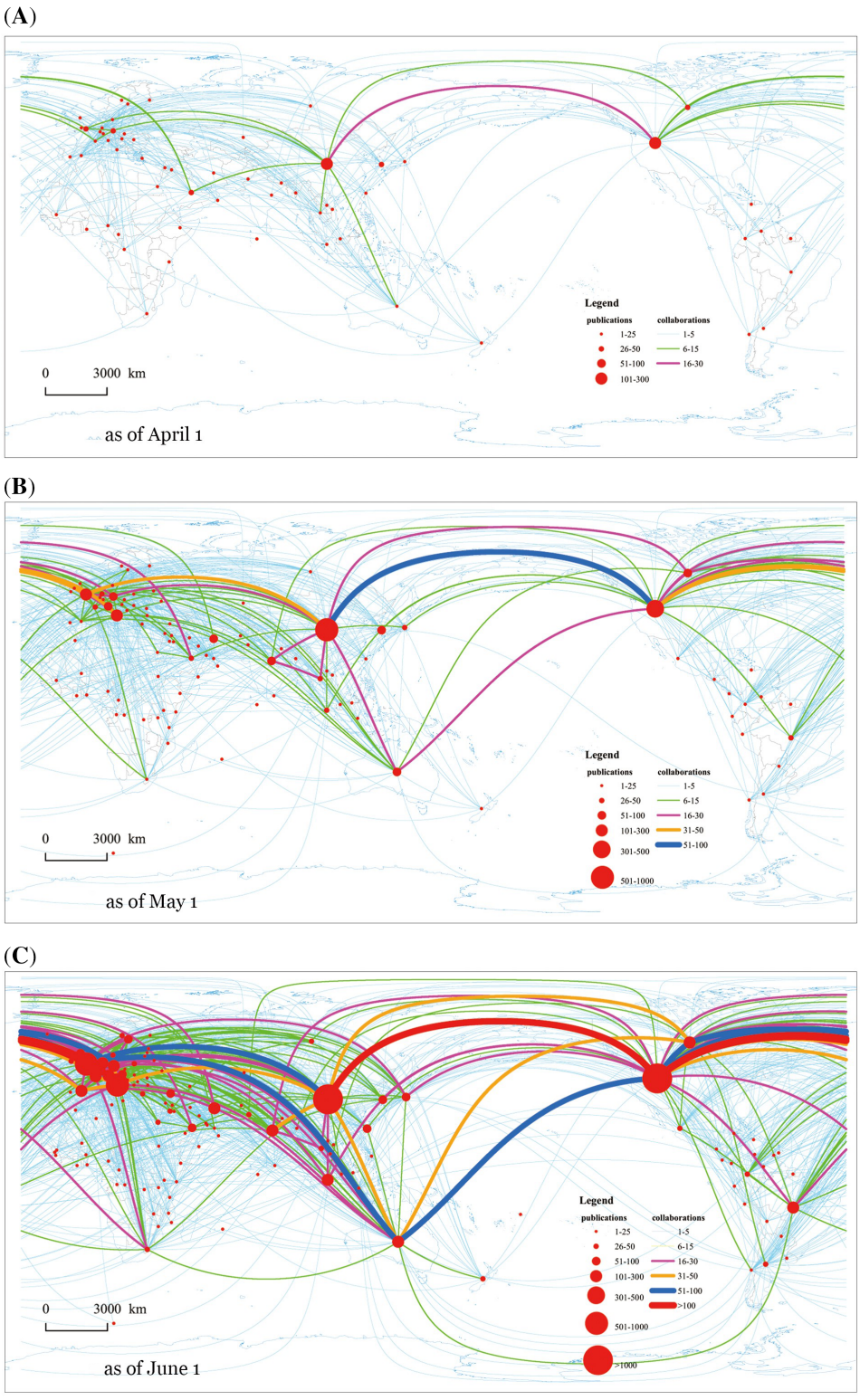



**FIGURE 2** Geographic pattern of international cooperation on COVID-19 research.

Canada in North America, India, Australia, Iran, Singapore, *etc*. in the Asia-Pacific, and Italy, Germany, France, Switzerland, *etc*. in Europe also greatly participate in scientific cooperation on COVID-19. However, as of now, China and the US are the two most important countries for COVID-19 research and scientific cooperation. At the five points in time, the closest cooperation

**TABLE 6** International cooperation on COVID-19 of main countries (regions).

| | As of April 1 | | As of May 1 | | As of June 1 | |
|---|---|---|---|---|---|---|
| Country/region | Partners | Collaborations | Partners | Collaborations | Partners | Collaborations |
| US | 35 | 112 | 70 | 476 | 95 | 1,304 |
| China | 31 | 132 | 52 | 353 | 72 | 776 |
| England | 28 | 77 | 60 | 351 | 84 | 972 |
| Italy | 21 | 40 | 47 | 245 | 67 | 710 |
| India | 7 | 16 | 41 | 120 | 63 | 289 |
| Germany | 30 | 69 | 51 | 215 | 72 | 575 |
| Canada | 22 | 57 | 45 | 171 | 68 | 514 |
| Australia | 20 | 39 | 36 | 153 | 60 | 472 |
| Iran | 2 | 2 | 26 | 52 | 46 | 145 |
| Switzerland | 19 | 28 | 42 | 121 | 61 | 360 |
| France | 17 | 38 | 37 | 120 | 52 | 374 |
| Singapore | 8 | 13 | 22 | 56 | 44 | 164 |
| South Korea | 13 | 14 | 28 | 62 | 37 | 115 |
| Brazil | 6 | 8 | 38 | 88 | 54 | 223 |
| Netherlands | 16 | 24 | 34 | 108 | 53 | 309 |
| Spain | 18 | 20 | 31 | 108 | 58 | 352 |
| Japan | 12 | 17 | 24 | 48 | 55 | 199 |
| Turkey | 0 | 0 | 2 | 2 | 39 | 87 |
| Saudi Arabia | 24 | 59 | 41 | 115 | 51 | 172 |
| Chinese Taiwan | 9 | 13 | 16 | 29 | 34 | 83 |

*Note:* "Partners" = number of countries (regions) they cooperated with, "Collaborations" = number of international collaborations.

relationship always existed between China and the US, increasing from 29 as of April 1 to 189 as of June 1.

## Contributing institutes

Chinese institutes also played an important role in promoting cooperation on COVID-19 among institutes. But over time, the role of institutes in the US (e.g. Harvard Medical School, HMS), Canada (e.g. University of Toronto, UT), England (e.g. University College London, UCL), Germany (e.g. Charité-University Medicine Berlin, CUMB), and Australia (e.g. University of Sydney, UoS) in scientific cooperation on COVID-19 also grew rapidly, even more than most institutes in China. Literature statistics as of April 1 showed that CAS and Capital Medical University (CMU) cooperated with 61 and 64 institutes 87 and 83 times, respectively, becoming the double-core of the inter-institute cooperation network on COVID-19. In addition, HUST, CUMB, UoS, and Fudan University (FU), carrying out 59, 58, 56, and 56 collaborations with 40, 38, 47, and 43 institutes, respectively, also played an important role in the scientific cooperation on COVID-19 (Table 8). Among the top 20 institutional partnerships, Chinese institutes participated in 9 of them. Cooperation between CAS and University of CAS (U. CAS) was the greatest with nine collaborations. By May 1, HKU, CMU, and HUST ranked among the top three with 187, 186, and 178 collaborations, respectively. Regarding the number of partners, HKU, UCL, and HUST ranked among the top three with 155, 126, and 119 partners, respectively. In addition, FU, WU, CAMS, and Oxford University (OU) also played an important role in promoting cooperation on COVID-19 between institutes. Among the top 20 institutional partnerships, there were 10 pairs with Chinese institute participation. The collaborations between CAS and U. CAS also ranked highest with 15 collaborations.

As of June 1, HUST and HMS had conducted 418 and 409 institutional collaborations, respectively. There are also 7 institutes that conducted more than 300 institutional collaborations, namely, UT, UCL, University of Melbourne (UMB), CUHK, Columbia University (CU), HKU, and WU. In terms of the number of partners, HMS, the only institute with more than 300 partners, has cooperated with 309 institutes. There are also 11 institutes with more than 200 partners, of which UT and UCL have more than 250 partners. Among the top 20 partnership institutes, there were 6 pairs of Chinese institutes' and 5 pairs from Germany. The collaborations between HUST and WU reached 22, ranking

**TABLE 7** Top 20 partnerships (country-level) with the most frequent cooperation on COVID-19.

| As of April 1 | | As of May 1 | | As of June 1 | |
|---|---|---|---|---|---|
| **Cooperation pairs** | **Times** | **Cooperation pairs** | **Times** | **Cooperation pairs** | **Times** |
| China and the US | 29 | China and the US | 86 | China and the US | 189 |
| The US and Saudi Arabia | 13 | The US and England | 45 | The US and England | 129 |
| China and England | 12 | China and England | 38 | The US and Italy | 102 |
| China and Canada | 11 | The US and Italy | 36 | The US and Canada | 89 |
| China and Australia | 10 | England and Germany | 26 | China and England | 88 |
| The US and Canada | 9 | China and Australia | 23 | England and Italy | 77 |
| The US and England | 9 | The US and Canada | 23 | The US and Australia | 70 |
| England and Germany | 8 | The US and Germany | 22 | The US and Germany | 59 |
| China and Germany | 7 | England and Italy | 21 | England and Germany | 58 |
| Canada and Saudi Arabia | 6 | The US and Australia | 20 | England and Australia | 52 |
| Germany and France | 6 | China and Canada | 20 | England and Canada | 52 |
| The US and France | 6 | China and India | 18 | China and Australia | 43 |
| China and Saudi Arabia | 6 | China and Germany | 17 | Italy and Germany | 43 |
| China and Thailand | 6 | India and Thailand | 17 | The US and France | 40 |
| Germany and Saudi Arabia | 5 | The US and Saudi Arabia | 17 | Italy and Spain | 40 |
| China and India | 5 | England and Canada | 16 | The US and Switzerland | 40 |
| India and Thailand | 5 | China and Thailand | 16 | China and Canada | 38 |
| China and Italy | 5 | Germany and Italy | 15 | China and India | 38 |
| Canada and Australia | 4 | The US and Switzerland | 15 | China and Italy | 35 |

highest among institutional cooperation. An interesting phenomenon is that, contrary to international cooperation, cooperation on COVID-19 among institutes exhibits significant geographic proximity, that is, inter-institute cooperation on COVID-19 mostly occurred within the country or even within the city. Among the top 20 institutional partnerships as of June 1, there was only one transnational partnership (Table 9).

## DISCUSSIONS AND CONCLUSIONS

At the time of writing, the COVID-19 pandemic is still ravaging the world. Tens of thousands of confirmed cases and thousands of deaths are confirmed and announced every day. More extensive and in-depth cooperation should be carried out on a global scale (Nature Editorial, 2020a, 2020b). This paper attempts to provide a comprehensive picture of scientific collaboration on COVID-19 research among countries/regions and among institutes within the first few months of the pandemic. The study included 5,827 papers about COVID-19 published by 6,349 institutions from 128 countries/regions.

We admit that there are some shortcomings in this study. Firstly, we limited our data to the publications retrieved from the Web of Science. Although it is known for its huge amount of data (Cassi *et al*., 2012; Gui *et al*., 2018b; Leydesdorff & Wagner, 2008), it is still limited in its inclusion. Secondly, although co-publications are widely accepted as proxies of scientific collaboration, as mentioned before, scientific cooperation does not necessarily lead to the publication of papers (Cantner & Rake, 2014; Royal Society, 2011). Moreover, cooperation in publishing papers may only be a small aspect of scientific cooperation on COVID-19. Thirdly, this paper mainly focused on the cooperation, other bibliometric features are not involved, such as citation analysis, hotspot analysis, and community analysis.

Through this bibliometric study, we found some interesting phenomena. First of all, scientific cooperation on COVID-19 has become more frequent. As of June 1, an increasing number of countries/regions, institutions, and researchers participated in scientific cooperation on COVID-19. The international scientific community generally recognizes that collaboration is the right way to work to overcome the epidemic and build a community of human health. Secondly, we discovered that the tri-polar pattern of international scientific cooperation controlled by North America, Asia-Pacific, and Europe (Gui, Liu, & Du, 2019; Gui, Liu, Du, *et al*., 2019) is clearly portrayed in COVID-19 research. In these three regions, the US, China, England, Canada, Germany, India, and Australia are the core hubs of the international cooperation network for COVID-19 research. Particularly, the US is playing an

**TABLE 8** The top 20 institutional cooperation on COVID-19.

| As of April 1 | | | As of June 1 | | |
|---|---|---|---|---|---|
| Institution | Partners | Collaborations | Institution | Partners | Collaborations |
| CAS | 61 | 87 | HUST | 235 | 418 |
| CMU | 64 | 83 | HMS | 309 | 409 |
| HUST | 40 | 59 | UT | 291 | 398 |
| CUMB | 38 | 58 | UCL | 254 | 362 |
| UoS | 47 | 56 | UMB | 244 | 343 |
| FU | 43 | 56 | CUHK | 223 | 338 |
| CUHK | 39 | 56 | CU | 244 | 324 |
| Ins. Pa | 50 | 55 | HKU | 224 | 315 |
| UT | 49 | 51 | WU | 186 | 306 |
| UCL | 33 | 49 | CMU | 174 | 295 |
| PU | 41 | 47 | UoS | 222 | 278 |
| ZJU | 41 | 47 | CUMB | 209 | 277 |
| AU | 34 | 47 | UoM | 215 | 271 |
| CAMS | 33 | 42 | OU | 189 | 268 |
| WU | 31 | 42 | UW | 194 | 266 |
| GMU | 39 | 41 | UP | 221 | 265 |
| HKU | 35 | 39 | CAMS | 159 | 260 |
| KAU | 30 | 38 | PU | 183 | 258 |
| EMU | 32 | 36 | FU | 140 | 236 |
| UW | 28 | 33 | UMG | 190 | 235 |

Abbreviations: AU, Alfaisal University; Ins. Pa, Institut Pasteur; KAU, King AbdulAziz University; UP, University of Pennsylvania; UW, University of Washington.

**TABLE 9** Top 20 partnerships (institute-level) with the most frequent cooperation on COVID-19.

| As of April 1 | | As of June 1 | |
|---|---|---|---|
| Cooperation pairs | Collaborations | Cooperation pairs | Collaborations |
| CAS and UCAS | 9 | HUST and WU | 22 |
| HU and JSTA | 7 | DDYPU and HMU | 20 |
| CUHK and UCL | 5 | CAS and UCAS | 16 |
| CICSPP and HZAU | 5 | SBUMS and UTMS | 16 |
| HUST and WU | 5 | CUHK and HKU | 14 |
| BIH and CUMB | 4 | BIH and GUMB | 13 |
| BIH and FUB | 4 | BIH and FUB | 13 |
| BIH and HBU | 4 | CMU and CAMS | 13 |
| CMU and CAMS | 4 | CUMB and HBU | 13 |
| CMU and HUST | 4 | FU and SJTU | 13 |
| CUMB and FUB | 4 | NUHS and NUS | 13 |
| CUMB and HBU | 4 | RMH and UMB | 13 |
| CAS and CCDCP | 4 | BIH and HBU | 12 |
| DDYPU and HMU | 4 | CUMB and FUB | 12 |
| FUB and HBU | 4 | FICGOMP and UoM | 12 |
| FU and NYBC | 4 | FUB and HBU | 12 |
| HZAU and UGA | 4 | IUMS and SBUMS | 12 |
| AU and CUHK | 3 | IUMS and UTMS | 12 |
| AU and EMU | 3 | CMU and HUST | 11 |

Abbreviations: BIH, Berlin Institute of Health; CCDCP, Chinese Center for Disease Control and Prevention; CICSPP, Cooperative Innovation Center for Sustainable Pig Production; FUB, Free University of Berlin; HBU, Humboldt—Universitat zu Berlin; IUMS, Iran University of Medical Sciences; JSTA, Japan Science and Technology Agency; UGA, University of Georgia.

increasingly important role in research and international cooperation on COVID-19, reflecting its status as a global scientific centre. Most countries/regions regard the US as the strongest scientific partner. Thirdly, China has played a vital role in the scientific research and cooperation on COVID-19, which is not only reflected in the number of published papers (Duan *et al*., 2020) but also in its extensive international cooperation (Mo & Zhou, 2020; Wu *et al*., 2020; Zhou *et al*., 2020). Fourth, China and the US were the closest partners in the current international scientific cooperation of COVID-19. Regardless of the current tense international relations between China and the US, in the face of the epidemic the institutions and researchers of the two countries still carried out close scientific cooperation.

## REFERENCES


Adams, J. (2013). Collaborations: The fourth age of research. *Nature*, *497*(7451), 557–560. https://doi.org/10.1038/497557a

Adams, J., & Loach, T. (2015). Comment: A well-connected world. *Nature*, *527*(7577), 558–559.

Aldridge, T. T., & Audretsch, D. (2011). The Bayh-Dole act and scientist entrepreneurship. *Research Policy*, *40*(8), 1058–1067. https://doi.org/10.1016/j.respol.2011.04.006

Andersen, L. E. (2019). The uneven space of scientific collaboration. *Metascience*, *28*, 459–461. https://doi.org/10.1007/s11016-019-00440-y

Ankrah, S., & Al-Tabbaa, O. (2015). Universities–industry collaboration: A systematic review. *Scandinavian Journal of Management*, *31*(3), 387–408. https://doi.org/10.1016/j.scaman.2015.02.003

Basu, A., & Kumar, B. S. V. (2000). International collaboration in Indian scientific papers. *Scientometrics*, *48*, 381–402. https://doi.org/10.1023/A:1005692505687

Bathelt, H., & Henn, S. (2014). The geographies of knowledge transfers over distance: Toward a typology. *Environment and Planning A: Economy and Space*, *46*(6), 1403–1424. https://doi.org/10.1068/a46115

Bauder, H., Lujan, O., & Hannan, C. A. (2018). Internationally mobile academics: Hierarchies, hegemony, and the geo-scientific imagination. *Geoforum*, *89*, 52–59. https://doi.org/10.1016/j.geoforum.2018.01.004

Bekkers, R., & Freitas, I. M. B. (2008). Analysing knowledge transfer channels between universities and industry: To what degree do sectors also matter? *Research Policy*, *37*(10), 1837–1853. https://doi.org/10.1016/j.respol.2008.07.007

Berkley, S. (2020). COVID-19 needs a Manhattan project. *Science*, *367*(6485), 1407. https://doi.org/10.1126/science.abb8654

Cantner, U., & Rake, B. (2014). International research networks in pharmaceuticals: Structure and dynamics. *Research Policy*, *43*(2), 333–348. https://doi.org/10.1016/j.respol.2013.10.016

Cassi, L., Morrison, A., & Rabellotti, R. (2015). Proximity and scientific collaboration: Evidence from the global wine industry. *Tijdschrift voor Economische en Sociale Geografie*, *106*(2), 205–219. https://doi.org/10.1111/tesg.12137

Cassi, L., Morrison, A., & Wal, A. L. J. T. (2012). The evolution of trade and scientific collaboration networks in the global wine sector: A longitudinal study using network analysis. *Economic Geography*, *88*(3), 311–334. https://doi.org/10.1111/j.1944-8287.2012.01154.x

Chen, K., Zhang, Y., & Fu, X. (2019). International research collaboration: An emerging domain of innovation studies? *Research Policy*, *48*(1), 149–168. https://doi.org/10.1016/j.respol.2018.08.005

Choi, S., Yang, J. S., & Park, H. W. (2015). The triple helix and international collaboration in science. *Journal of the Association for Information Science and Technology*, *66*(1), 201–212. https://doi.org/10.1002/asi.23165

Corey, L., Mascola, J. R., & Fauci, A. S. (2020). A strategic approach to COVID-19 vaccine R&D. *Science*, *368*, 948–950. https://doi.org/10.1126/science.abc5312

Drew, D. A., Nguyen, L. H., Steves, C. J., Menni, C., Freydin, M., Varsavsky, T., Sudre, C. H., Cardoso, M. J., Ourselin, S., Wolf, J., Spector, T. D., Chan, A. T., & COPE Consortium§. (2020). Rapid implementation of mobile technology for real-time epidemiology of COVID-19. *Science*, *368*, 1362–1367. https://doi.org/10.1126/science.abc0473

Duan, D., Chen, Y., & Zhang, Y. (2020). Who is contributing? Scientific collaborations on COVID-19. *Environment and Planning A: Economy and Space*, *52*, 1487–1489. https://doi.org/10.1177/0308518X20931105

Freeman, R. B. (2010). Globalization of scientific and engineering talent: International mobility of students, workers, and ideas and the world economy. *Journal of Economics of Innovation and New Technology*, *19*(5), 393–406. https://doi.org/10.1080/10438590903432871

Fung, H., & Wong, C. (2017). Scientific collaboration in indigenous knowledge in context: Insights from publication and co-publication network analysis. *Technological Forecasting and Social Change*, *117*, 57–69. https://doi.org/10.1016/j.techfore.2017.01.009

Gauffriau, M., & Larsen, P. (2005). Counting methods are decisive for rankings based on publication and citation studies. *Scientometrics*, *64*, 85–93. https://doi.org/10.1007/s11192-005-0239-6

Gazni, A., Sugimoto, C. R., & Didegah, F. (2012). Mapping world scientific collaboration: Authors, institutions, and countries. *Journal of the American Society for Information Science and Technology*, *63*(2), 323–335. https://doi.org/10.1002/asi.21688

Guan, W., Ni, Z., Hu, Y., Liang, W. H., Ou, C. Q., He, J. X., Liu, L., Shan, H., Lei, C. L., Hui, D. S. C., du, B., Li, L. J., Zeng, G., Yuen, K. Y., Chen, R. C., Tang, C. L., Wang, T., Chen, P. Y., Xiang, J., … China Medical Treatment Expert Group for Covid-19. (2020). Clinical characteristics of coronavirus disease 2019 in China. *The New England Journal of Medicine*, *382*, 1708–1720. https://doi.org/10.1056/NEJMoa2002032

Gui, Q., Liu, C., & Du, D. (2018a). Does network position foster knowledge production? Evidence from international scientific collaboration network. *Growth and Change*, *49*(3), 532–547. https://doi.org/10.1111/grow.12245

Gui, Q., Liu, C., & Du, D. (2018b). International knowledge flows and the role of proximity. *Growth and Change*, *49*(4), 594–611. https://doi.org/10.1111/grow.12263

Gui, Q., Liu, C., & Du, D. (2019). Globalization of science and international scientific collaboration: A network perspective. *Geoforum*, *105*, 1–12. https://doi.org/10.1016/j.geoforum.2019.06.017

Gui, Q., Liu, C., Du, D., et al. (2019). The changing geography of global science. *Environment and Planning A: Economy and Space*, *51*(8), 1615–1617. https://doi.org/10.1177/0308518X18816694

He, T. (2009). International scientific collaboration of China with the G7 countries. *Scientometrics*, *80*, 571–582. https://doi.org/10.1007/s11192-007-2043-y

Hou, H., Kretschmer, H., & Liu, Z. (2008). The structure of scientific collaboration networks in Scientometrics. *Scientometrics*, *75*, 189–202.

Lemarchand, G. A. (2012). The long-term dynamics of co-authorship scientific networks: Iberoamerican countries (1973–2010). *Research Policy*, *41*(2), 291–305. https://doi.org/10.1016/j.respol.2011.10.009

Leydesdorff, L., & Wagner, C. S. (2008). International collaboration in science and the formation of a core group. *Journal of Informetrics*, *2*(4), 317–325. https://doi.org/10.1016/j.joi.2008.07.003

Liu, C., & Gui, Q. (2016). Mapping intellectual structures and dynamics of transport geography research: A scientometric overview from 1982 to 2014. *Scientometrics*, *109*, 159–184. https://doi.org/10.1007/s11192-016-2045-8

Mo, J., & Zhou J. (2020). Xi vows to back nations' virus fight. *China Daily*, April 11.

Narin, F., Stevens, K., & Whitlow, E. S. (1991). Scientific co-operation in Europe and the citation of multinationally authored papers. *Scientometrics*, *21*, 313–323. https://doi.org/10.1007/BF02093973

Nature Editorial. (2020a). Calling all coronavirus researchers: Keep sharing, stay open. *Nature*, *578*, 7.

Nature Editorial. (2020b). Coronavirus: Three things all governments and their science advisers must do now. *Nature*, *579*, 319–320.

Nature Editorial. (2020c). Coronavirus: Everyone wins when patents are pooled. *Nature*, *581*, 240.

Nature Medicine Editorial. (2020). Communication, collaboration and cooperation can stop the 2019 coronavirus. *Nature Medicine*, *26*, 151.

Nemeth, R. J., & Smith, D. A. (1985). International trade and world-system structure: A multiple network analysis. *Review (Fernand Braudel Center)*, *8*(4), 517–560.

Perianes-Rodriguez, A., Waltman, L., & Van Eck, N. J. (2016). Constructing bibliometric networks: A comparison between full and fractional counting. *Journal of Informetrics*, *10*(4), 1178–1195. https://doi.org/10.1016/j.joi.2016.10.006

Royal Society. (2011). *Knowledge, networks and nations: Global scientific collaboration in the 21st century*. London, England: The Royal Society.

Smith, D. A., & White, D. R. (1992). Structure and dynamics of the global economy: Network analysis of international trade 1965–1980. *Social Forces*, *70*(4), 857–893. https://doi.org/10.2307/2580193

Sun, Y., & Cao, C. (2020). The dynamics of the studies of China's science, technology and innovation (STI): A bibliometric analysis of an emerging field. *Scientometrics*, *124*, 1335–1365. https://doi.org/10.1007/s11192-020-03500-x

Sun, Y., & Grimes, C. (2016). The emerging dynamic structure of national innovation studies: A bibliometric analysis. *Scientometrics*, *106*, 17–40. https://doi.org/10.1007/s11192-015-1778-0

Tian, H., Liu, Y., Li, Y., Wu, C. H., Chen, B., Kraemer, M. U. G., Li, B., Cai, J., Xu, B., Yang, Q., Wang, B., Yang, P., Cui, Y., Song, Y., Zheng, P., Wang, Q., Bjornstad, O. N., Yang, R., Grenfell, B. T., … Dye, C. (2020). An investigation of transmission control measures during the first 50 days of the COVID-19 epidemic in China. *Science*, *368*(6491), 638–642. https://doi.org/10.1126/science.abb6105

Van Eck, N. J., & Waltman, L. (2010). Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*, *84*, 523–538. https://doi.org/10.1007/s11192-009-0146-3

Van Eck, N. J., Waltman, L., Dekker, R., & van den Berg, J. (2010). A comparison of two techniques for bibliometric mapping: Multidimensional scaling and VOS. *Journal of the American Society for Information Science and Technology*, *61*(12), 2405–2416.

Wagner, C. S., Whetsell, T. A., & Mukherjee, S. (2019). International research collaboration: Novelty, conventionality, and atypicality in knowledge recombination. *Research Policy*, *48*(5), 1260–1270. https://doi.org/10.1016/j.respol.2019.01.002

Wallerstein, I. (1974). *The modern world system*. New York, NY: Academic Press.

Waltman, L., Van Eck, N. J., & Noyons, E. C. M. (2010). A unified approach to mapping and clustering of bibliometric networks. *Journal of Informetrics*, *4*(4), 629–635. https://doi.org/10.1016/j.joi.2010.07.002

Washington, H. A. (2020). How environmental racism is fuelling the coronavirus pandemic. *Nature*, *581*, 241. https://doi.org/10.1038/d41586-020-01453-y

Watts, D. J., & Strogatz, S. H. (1998). Collective dynamics of 'small-world' networks. *Nature*, *393*, 440–442. https://doi.org/10.1038/30918

Wu, F., Zhao, S., Yu, B., Chen, Y. M., Wang, W., Song, Z. G., Hu, Y., Tao, Z. W., Tian, J. H., Pei, Y. Y., Yuan, M. L., Zhang, Y. L., Dai, F. H., Liu, Y., Wang, Q. M., Zheng, J. J., Xu, L., Holmes, E. C., & Zhang, Y. Z. (2020). A new coronavirus associated with human respiratory disease in China. *Nature*, *579*, 265–269. https://doi.org/10.1038/s41586-020-2008-3

Wuestman, M. L., Hoekman, J., & Frenken, K. (2019). The geography of scientific citations. *Research Policy*, *48*(7), 1771–1780. https://doi.org/10.1016/j.respol.2019.04.004

Zhou, P., Yang, X., Wang, X., Hu, B., Zhang, L., Zhang, W., Si, H.-R., Zhu, Y., Li, B., Huang, C.-L., Chen, H.-D., Chen, J., Luo, Y., Guo, H., Jiang, R.-D., Liu, M.-Q., Chen, Y., Shen, X.-R., Wang, X., … Shi, Z.-L. (2020). A pneumonia outbreak associated with a new coronavirus of probable bat origin. *Nature*, *579*, 270–273. https://doi.org/10.1038/s41586-020-2012-7

Zhu, N., Zhang, D., Wang, W., Li, X., Yang, B., Song, J., Zhao, X., Huang, B., Shi, W., Lu, R., Niu, P., Zhan, F., Ma, X., Wang, D., Xu, W., Wu, G., Gao, G. F., Tan, W., & China Novel Coronavirus Investigating and Research Team. (2020). A novel coronavirus from patients with pneumonia in China, 2019. *The New England Journal of Medicine*, *382*, 727–733. https://doi.org/10.1056/NEJMoa2001017