Structural Change and Economic Dynamics 69 (2024) 281–297

Contents lists available at ScienceDirect

Structural Change and Economic Dynamics

journal homepage: www.elsevier.com/locate/strueco

Changing structures in transnational research networks: An analysis of the impact of COVID-19 on China's scientific collaborations

Lauretta Rubini [a,b,*], Chiara Pollio [a,b], Elisa Barbieri [b,c], Sebastiano Cattaruzzo [b,c]

[a] Università degli Studi di Ferrara, Italy
[b] CiMET – Centro Universitario Nazionale di Economia Applicata, Italy
[c] Università Ca' Foscari di Venezia, Italy

ARTICLE INFO

Keywords:
Transnational research networks
COVID-19
China
U.S.
SNA
Scientific collaborations

ABSTRACT

Research networks play pivotal roles in the creation and diffusion of knowledge. It is widely acknowledged that frontier research tends to cluster around transnational research networks (TRNs), which also represent strategic tools for nurturing innovation in R&D-intensive companies. Therefore, they are crucial for promoting the rapid development of the knowledge economy in underdeveloped countries.

In this context, China's experience is particularly relevant because the country has invested heavily in knowledge production, which is arguably one of the most important structural changes at the global level in recent decades, with important implications for the division of labor and trade among countries. The country has been investing in order to become the scientific world leader, and in this transition, research collaboration, in particular with other countries, can become strategic. In this work, we analyze whether COVID-19 and related research have affected the shape of the network and the intensity of collaborations involving China in the field of health studies, comparing it to the case of the U.S. as the global leader in research (Fry et al., 2020). In particular, we wish to assess whether COVID-19-related research has pushed toward larger and more intensive collaborations internationally than before the pandemic or whether a tendency to closure has prevailed has prevailed. This also means understanding whether COVID-19, as a global phenomenon, has affected China in rising as an international research leader. To do so, we built an original dataset of international, coauthored publications involving China or the U.S. in selected health research fields. Our analysis first shows that COVID-19 research has assumed specific features distinct from other topics in the same research field, shaping research networks in a peculiar way for both China and the U.S. Second, for China, COVID-19 does not appear to have represented an opportunity to further climb up the international research ladder, as it has attracted a relatively low and more volatile number of collaborators from different countries.

1. Introduction

A growing body of literature looks at research networks as indicators of larger collaboration networks fostering the spread of knowledge and innovation in the context of production (Sonnenwald, 2007; Adams, 2013; Di Cagno et al., 2014; Adams and Loach, 2015; Gui et al., 2019). Such aspects have been underlined both in the case of local networks and, more importantly, in relation to networks involving actors spread across different countries. Consistent with the potential of such networks to generate and diffuse innovation, the policies aimed at supporting them can be regarded as industrial and innovation policies (Clark, 2010).

It is increasingly recognized that the "evolution of research networks between countries or institutions is of more than academic interest", particularly given that "the leading edge of scientific discovery is now in the realm of international collaboration networks rather than individuals, institutions or nations" (Adams and Loach, 2015).

Frontier research, especially in the natural sciences, tends to cluster around specific transnational research networks (hereafter referred to as TRNs), which also include the collaboration of large R&D intensive multinational companies (Nature, 2015). In this framework, TRNs become an important form of infrastructure potentially nurturing innovation in large R&D-intensive transnational companies. Therefore, being inside or outside such networks seems crucial for countries aiming

* Corresponding author.
E-mail address: rbnltt@unife.it (L. Rubini).

https://doi.org/10.1016/j.strueco.2023.12.018
Received 8 August 2023; Received in revised form 18 December 2023; Accepted 31 December 2023
Available online 1 January 2024

at catching-up in the "knowledge economy". Furthermore, as noted in Lundvall & Rikap (2022) and previously noted in Freeman (2002), technological and knowledge revolutions are primary means of facilitating change in world economic leadership; these revolutions are intrinsically temporal phenomena, and in this case, the ability to establish an efficient and extensive research network is certainly of utmost importance. Some countries have attempted to build catch-up strategies by targeting transnational research networks (Rikap and Flacher, 2020).

In this context, the experience of China's catching up is particularly relevant because of the transition's speed, characteristics and implications for the world economy (Xie and Freeman, 2019; Freeman, 2002; Lundvall and Rikap, 2022; Di Tommaso et al., 2013, 2020). In particular, as noted by Xie and Freeman (2019), China has invested heavily in achieving a comparative advantage in knowledge, and this is arguably one of the most important structural changes at the global level in recent decades, with important implications for the division of labor and trade among countries.

International collaborations can be more relevant when we look at specific sectors. Health is usually regarded as one of those areas of knowledge, research, and production in which international collaboration can indeed assume a strategic role (Ellemers, 2021). In this work, we examine the role that the COVID-19 pandemic has played in affecting transnational collaborations in the field of medical studies. Given that this has been an unprecedented event in the recent history of global health, we would expect a greater tendency of countries to coordinate scientific efforts to collectively achieve outcomes that would otherwise be impossible to reach individually (Jit et al., 2021).

The first available studies on this topic reached contrasting conclusions. On the one hand, while some authors have indeed identified an increasing propensity for international collaboration, especially immediately after the outbreak of the pandemic. For example, Lee and Haupt (2021) have found that countries have increased the international partnerships during the pandemic period, in particular on COVID publications, even if with different intensities. In particular, those that have participated more in transnational scientific research are the nations with relatively lower GDP. Duan and Xia (2021) also found an increasing tendency to international collaboration for COVID-related publications, but the social network analysis they performed highlighted that there is a concentration of research in few countries/regions. China has played a central role in favoring transnational collaboration especially at the outbreak of the pandemic, but such role seems to have become more blurred in the following phases (Duan and Xia, 2021; Cai et al., 2021). On the other hand, it is also possible to find works underlining an extreme heterogeneity in national behaviors, with a general tendency in the longer run towards a decrease in collaborations (Abramo et al., 2022). Even if international collaboration is seen as crucial to overcome worldwide emergencies (the Secretary-General of the United Nations Conference on Trade and Development stated that "It is thus crucial that scientific responses are based on international collaboration that brings together the best minds and available data from different countries for the benefit of all" (Kituyi, 2020), many countries seem to show reluctance to share data and competences, following a behavior that has been defined as "scientific nationalism" and that aims at jealously guarding the national competences in order to protect the national security and prestige and strengthen the competitive advantage (Lee and Haupt, 2021).Our analysis will focus on the case of China. The country is particularly interesting in this regard not only because it is the place where the virus originated and can therefore represent a particularly significant case study when dealing with COVID-19 but also because it places itself as an emerging player in the field of international research.

We analyze whether COVID-19 and related research have affected the shape of the network and the intensity of collaborations involving China in the field of health, comparing it to the case of the U.S. as the global leader in research (Fry et al., 2020). In particular, we wish to assess whether COVID-19-related research has pushed toward larger and more intensive collaborations internationally or whether tendencies to closure have prevailed. With respect to China, this also means understanding whether COVID-19, as a global phenomenon, has affected the rise of China as an international research leader.

We focus on the different degrees of participation of countries in the two networks before and after the pandemic. To do so, we built an original dataset of international multi-authored publications involving China or the U.S. in selected health research fields. These two countries are the main global players in scientific research and have also engaged in the highest number of joint studies on the topic (Lee and Haupt, 2021).

Our analysis shows that COVID-19 research has different features from those of other topics in the same research field, shaping research networks in a peculiar way for both China and the U.S. In addition, for China, COVID-19 does not appear to have represented an opportunity to further climb up the international research network. In fact, it has attracted collaborators from a relatively low number of countries and in a more volatile set of relationships.

The contribution of this paper is threefold.

First, understanding what has happened to international research in the case of COVID-19, especially in terms of the closure/enlargement of research networks, can provide relevant insights into what might be the future trends of international research in what has been called a new pandemic era (The Lancet Planetary Health, 2021; Daszak et al. 2020).

Second, more generally, the results of this analysis can elucidate which tendencies might occur in international collaborations when they are hit by unexpected systemic shocks and what the capacity of the global system is to face them in an open and collaborative way rather than with a closed and distrustful attitude. This has become particularly crucial in the recent era, in which societies are confronted with high uncertainty related to global political instability, climate change, and an increasing likelihood of similar situations emerging in the future (Marani et al., 2021; Haileamlak, 2022).

Finally, given the aim of China to become a technological leader by 2050, this study can contribute to the discussion about the role of the country as a global player in research and about its ability to catalyze international collaborations on relevant issues.

The remainder of the paper is organized as follows: the next paragraph introduces the relevant literature on research networks and their linkages with innovation and production, as well as reports that debate the role of China in health research and the impact of COVID-19 on health studies. Section 3 explains the methodological steps and the construction of the database on which we base our results, which are treated in Section 4 together with several robustness checks. Finally, Section 5 concludes with final remarks, policy implications and implications for future research.

2. Literature review

International collaboration plays a fundamental role in complementing national innovation systems for catching-up and economic growth (Jang and Ko, 2019).

COVID-19, as a recent health emergency, has spurred an unprecedented increase in pandemic-related publications, especially, though not exclusively, in the science and health fields, which also played a key role in the development of solutions to overcome it (Zhang et al., 2020; Fry et al., 2020). In more detail, a substantial amount of scientific contributions have been written (and published) either in the early phases of the pandemic or with it still ongoing (2019–2021), while fewer authors have been engaged in *ex post* appraisals.

Starting from the quasilive chronicle of the pandemic, Aviv-Reuven and Rosenfeld (2021) highlighted how the pandemic induced less international collaboration and faster publication of COVID-19-related papers, partially at the expense of non-COVID-19 papers. The closed nature of transnational coauthorships is also confirmed by Cai et al. (2021), who underline how, in this context, fewer nations and smaller

teams have been involved. This latter fact was also verified by Cunningham et al. (2021). Cai et al. (2021) also highlight the temporal alignment of publication intensity and COVID-19 incidence in the country. This fact is in line with findings of Wagner et al. (2022), who also emphasize how lower-income nations tend to be excluded from these specific research networks. Nevertheless, Sachini et al. (2021), studying Greek publications in particular, suggest that in some cases, the pandemic increased transnational collaboration. Additionally, Duan and Xia (2021) confirm this, despite the considerable regionalization of related research, following a clear core–periphery structure. Finally, Gao et al. (2021) study the possible long-term effects and establish that the pandemic did not structurally increase the amount of time spent on research but rather decreased the likelihood of pursuing new research projects.

Switching to *ex post* evaluations, Carvalho et al. (2023) suggested that the pandemic event induced the academic community to reduce traditional power disparities, promoting enhanced globalism in scientific endeavors. These findings are also partially confirmed by Xu et al. (2023), who found that the pandemic induced more collaboration between star scientists and newcomers, which ultimately reduced collaboration disparity. Carvalho et al. (2023) also stress the relevance of countries such as the U.S., China, Great Britain, and India in COVID-19-related publications, with India playing an especially prominent role in vaccine-related research (Zhao et al., 2022). To account for the existing heterogeneity in COVID-19-related collaboration patterns, Abramo et al. (2022) showed that overall, the pandemic significantly spurred national collaboration, while international collaboration is subject to important variations among countries.

A final note regards how the knowledge base evolved during the pandemic. Zhang et al. (2021) find that some COVID-19-related research lines returned to basic research pursued earlier, while others undertook new paths. Zhang et al. (2023) further elaborate on the phenomenon of studying the patterns of referencing and find that authors, especially in the early phases, have been mostly relying on and citing unconsolidated research.

Two possible trends might be in place. On the one hand, countries might have engaged in more intensive collaborations in pandemic-related topics than in similar fields of research since there has been a common global interest in fighting the pandemic (Duan and Xia, 2021).

Especially in the initial phase, there has been a strong emphasis posed on the need for international collaboration, in order to solve a disease that spread very rapidly outside the national boundaries (Mohamed et al., 2020). New data and research results have been rapidly shared worldwide, also thanks to the availability of open access servers and to the decision of some major high-tech companies, such as Microsoft or Amazon to temporarily grant free access to their patent libraries related to COVID (Kinsella et al., 2020). Scientists have been learning from each other thanks to an unprecedented availability of shared data and publications on the pandemic (Banda et al., 2021).

On the other hand, competitive and selective approaches to the research might have prevailed. Given the importance that discoveries related to the pandemic might have had, especially in the peak period, logics related to "scientific nationalism" might have emerged. Scientific findings might, in fact, make the difference in terms of national competitiveness, especially in times of uncertainty, and governments might be induced to reduce the collaboration intensity with other countries in order to avoid information leaks (Sá and Sabzalieva, 2018). A similar approach has hindered the institution of a steady inter-country collaboration for the development of common vaccines. This tendency, which has been called "vaccine nationalism", has been aimed at obtaining a preferential access to emerging COVID-19 vaccines, and has showed in a dramatic way the existence of strong closure forces acting even in a world-wide event such as a pandemic (Kharkevich and Zinovieva, 2022; (Zhou, 2021; Bollyky and Bown, 2020). Finally, another obstacle to the diffusion of scientific collaboration in COVID-related research might have been the different policy approaches to the management of the pandemics and its effects (Fry et al., 2020; Wagner et al., 2021). Countries have applied different measures, with a heterogeneous degree of severity, ranging from containment and closure policies, economic policies, health system policies and/or vaccination policy (Ma et al., 2021; Gros et al., 2021). In particular, China has been the country with the longest period of lockdown, and this might have had an impact on factors such as the mobility of researchers and the willingness to share strategic information.

Recent research has highlighted the importance of understanding the long-lasting effects of COVID-19 on China, pointing out the structural changes that can be observed within China's economy due to COVID-19. Han (2022), in particular, underlines the growth of scientific research and information transmission to the detriment of other sectors, such as petroleum and finance. Scientific collaboration and information transmission are encouraged by their significantly improved capacity to promote the development of connected upstream and downstream sectors. Researchers conclude that policies supporting scientific research and information transmission are potential long-term drivers of Chinese growth.

Within this framework, it is important to understand whether COVID-19 has significantly changed the pattern of international scientific collaboration in China. The country represents a particularly interesting case study in this field, given that contrasting forces might be in place. First, as the place from which the virus originally spread, China might have induced greater international interest in collaboration to study the origins of the pandemic and determine possible treatments. Second, China is undoubtedly an emerging actor in transnational research networks in general and in the health field specifically. The increasing international scientific role of the country might also have led to greater interest in international collaboration. In contrast, the country has applied a unique policy mix to fight COVID-19, using widespread and intensive measures including lockdowns and Zero-COVID tolerance and showing a different attitude toward vaccines.[1–4] This approach might have instead reduced the propensity of scientists to adopt international collaboration in this field. Our study aimed to shed some light on the possible results of these contrasting forces.

3. Methodology

Our research aim is to analyze the effects of COVID-19 on Chinese health research networks using the U.S. as a comparison case. To do so, we choose coauthored publications as a proxy of research collaboration. While some doubts arise regarding the opportunity to use these tools to investigate the quality of research (Schmoch and Schubert, 2007), coauthorship is one of the most utilized indicators in the literature for investigating the mechanisms that shape the scientific community, which is increasingly oriented toward collaboration (Kumar, 2015). According to our framework, a transnational research network involving China/the U.S. consists of a group of coauthored publications (nets) in which there is at least one author with a Chinese/U.S. affiliation and at least another author with a foreign affiliation.

Various international repositories collect information about coauthored publications. Among these, we have referred to Clarivate Analytics's Web of Science (WoS), the world's leading scientific citation search and analytical information platform, as a main data reference. Starting from the information on publications in that database, we constructed an original dataset of international coauthored publications involving China or the U.S. in selected health research fields.

We adopted both intertemporal and intersectoral perspectives.

[1] Vaccination has never been mandatory in China, and the promotional campaign for elderly groups only started at the end of 2021 (Davidson, 2022). Furthermore, China refused the use of foreign-made vaccines, and started exclusively using a nationally produced vaccine in March 2023 (Hong and Stevenson, 2023).

Table 1
TOP5 Web of Science Categories (in terms of COVID-19 incidence).

	Web of Science Categories	Total publications	Publications on COVID-19	COVID-19 Incidence
	China			
TOP 5	Infectious Diseases	3109	618	19.88 %
	Health Policy Services	926	173	18.68 %
	Virology	1582	284	17.95 %
	Public Environmental Occupational Health	7390	1170	15.83 %
	Psychology Clinical	599	84	14.02 %
	US			
TOP 5	Virology	3155	631	20.00 %
	Infectious Diseases	9983	1944	19.47 %
	Primary Health Care	1055	175	16.59 %
	Medical Informatics	3524	553	15.69 %
	Public Environmental Occupational Health	26,695	3680	13.79 %

Source: Authors' elaboration of WoS data.

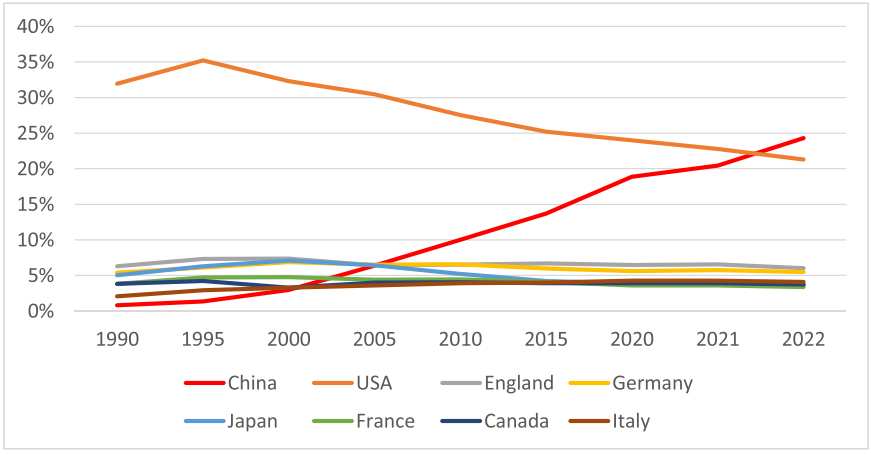

Fig. 1. Weights of the total publications in international journals in the selected nations.
Source: Authors' elaborations of WoS data.

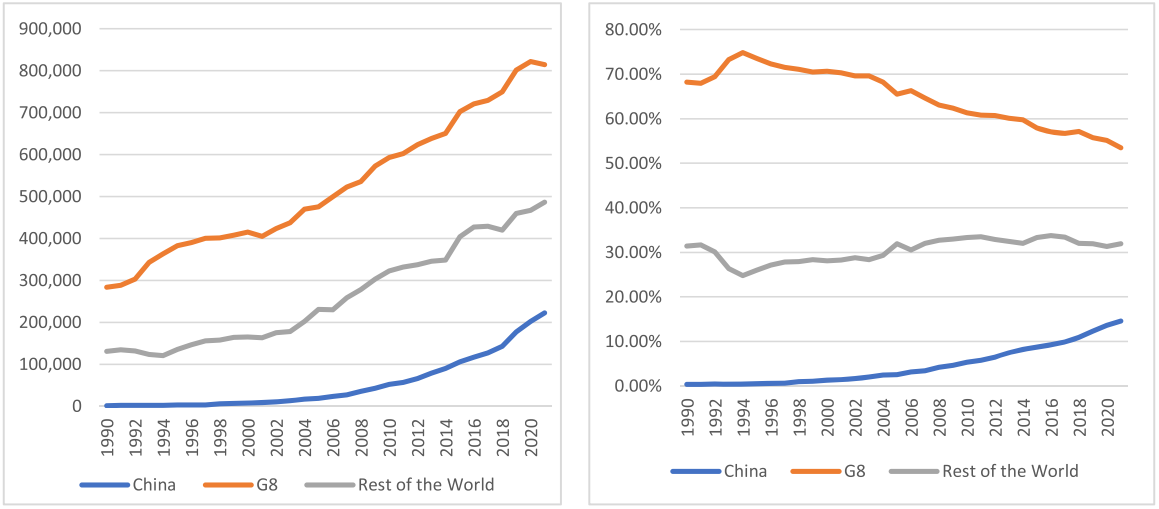

Fig. 2. Publications in health-related sectors.
Source: Authors' elaborations of WoS data.

In addition to this, we compare COVID-19 related publications with non-COVID ones in those health research areas in which COVID-19 had a higher research intensity.

For the inter-temporal dimension, we compare the research networks *before* and *after* the COVID-19 outbreak. The first cases of COVID-19 in China are dated between October and November 2019 (Roberts et al., 2021), while it was officially recognized a pandemic in March 11, 2020 (Cucinotta and Vanelli, 2020). This led us to set 2018 as observation year before the pandemic. As for the observation year after the pandemic, this same timeline suggests to exclude 2020, to avoid biasing downward the intensity at which international research networks have started focusing on the disease. In addition, if we look at the trend of

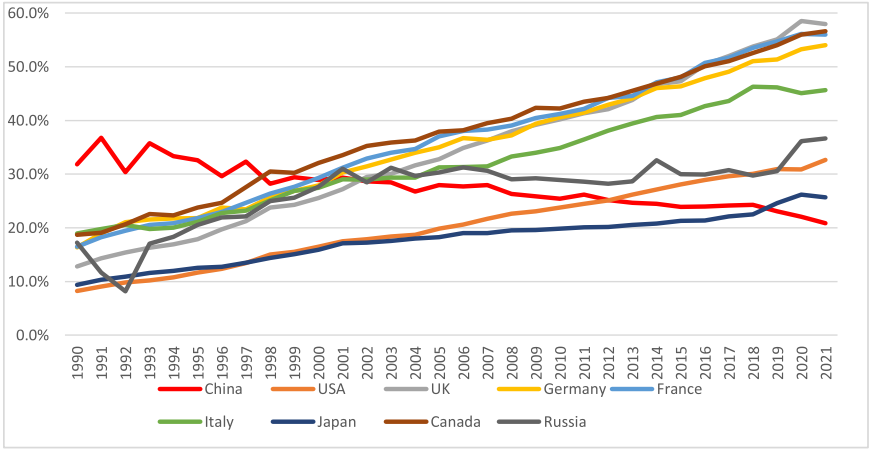

Fig. 3. Share of health-related publications published in collaboration with other countries.
Source: Authors' elaborations of WoS data.

Table 2
Number of publications in each subset.

	2018_TOP5	2021_TOP5		
		Tot	Of which TOP5_COV	Of which TOP5_NoCOV
China (total)	*6979*	*14,593*	*2342*	*12,171*
of which				
only Chinese affiliations	5011 (71.80 %)	10,999 (75.37 %)	1704 (72.76 %)	9215 (75.71 %)
Internationally co-authored	1968 (28.20 %)	3594 (24.63 %)	638 (27.24 %)	2956 (24.29 %)
U.S. (total)	*30,992*	*43,308*	*6781*	*36,527*
of which				
only U.S. affiliations	23,358 (75.37 %)	31,515 (72.77 %)	5041 (74.34 %)	26,474 (72.48 %)
Internationally co-authored	7634 (24.63 %)	11,793 (27.23 %)	1740 (25.66 %)	10,053 (27.52 %)

Source: Authors' elaborations of WoS data.

Table 3
Number of countries participating in COVID-19 and non-COVID-19 networks within the 2021_TOP5 sets.

	2021_TOP5	2021_TOP5_COV	2021_TOP5_NoCOV	COVID/Non COVID-19 difference
U.S.	188	154	185	−17 %
China	150	100	141	−29 %

Source: Authors' elaboration of WoS data.

COVID-19 related publications on Web of Science database, we observe the following: around 86,000 papers were published in 2020; almost 148,000 in 2021, and about 126,000 in 2022.[2] In other words, the number of COVID-19 papers reached a peak in 2021, while a year after a 14,9 % decrease occurred. This is consistent with the general behavior of health science journals, which dedicated specific fast tracks to COVID-19-related publications during the pandemics to speed up the knowledge and information circulation about an urgent global health issue. Empirical evidence has in fact shown that COVID-19-related papers have benefited from expedite review tracks with respect to non-COVID-19 researches (estimated to 11.3 days for the former vs 106.3 days for the latter, Putnam et al., 2020; see also Kodvanj et al., 2022). This rapid review and publication process minimizes the time-lag effects related to the publishing process. All such data have led us to select 2021 as the observation year after the pandemic.

More details about the inter-sectoral dimension, as well as the several steps followed to build the database are thoroughly described in the following section.

3.1. Building the database

The procedure used for building China's and the U.S.'s databases is as follows:

1. Identification of all the publications in WoS with at least one author with a Chinese/U.S. affiliation in health-related scientific fields in 2021. The Web of Science Categories included in the health sector are listed in Appendix 1.
2. To identify the health research fields that were most involved in COVID-19 research, all COVID-19-related publications in health studies were identified through an iterative keyword search. More precisely, first, the most common keywords related to COVID-19 used by the authors were identified and then progressively enlarged with the snowball sampling technique (including abbreviations and synonyms). The search was performed both in the keyword field and in the title to ensure that the highest possible number of COVID-19-related studies was included.
3. The first 5 health-related sectors according to the incidence of COVID-19 in 2021 (top 5) were selected for China and the U.S. (Table 1). While these sectors differ in terms of construction between the two countries, both countries had quantities of COVID-19-related

[2] Data observed on June 1st, 2023.

Table 4
Average number of authors and countries for international coauthored publications.

	Avg. N of countries/ publication		Avg. N of authors/ publication	
	China	USA	China	USA
2018_TOP5	3.07	2.88	12.17	9.67
2021_TOP5	2.88	2.94	9.06	9.82
2021_TOP5_COV	2.95	3.08	9.35	10.58
2021_TOP5_NoCOV	2.87	2.91	9.00	9.69

Source: Authors' elaboration of WoS data.

publications that represented between 14 % and 20 % of the total publications in the top 5 research areas.

4. Once the most COVID-19-impacted research fields were identified, the publication groups upon which the analysis was run were built, and all WoS publications in the "TOP 5″ sectors were downloaded, both for 2021 and for 2018. This process resulted in the use of two databases for each country: a) 2021 TOP 5 publications (2021_TOP5) and b) publications in the same sectors in 2018 (2018_TOP5).
5. For 2021, using the technique described in point 2, the sectors with a high incidence of COVID-19 topics were split into two further separate groups: those focused on COVID-19 (2021_TOP5_COV from now on) and those dealing with other issues (2021_TOP5_NoCOV).
6. Finally, for all the publications included in these groups and subgroups (95,872), we identified a) the authors' affiliations and countries involved in the collaboration, b) the number of affiliations coming from each country, and c) the total number of authors. In this way, it has been possible to separate the publications produced solely by the Chinese/U.S. authors from the transnational literature.
7. For each country, a) a 2018 set made of all coauthored publications in the top 5 health-related sectors was built; b) a similar 2021 set was built; and c) finally, the top 5 2021 sets were divided into COVID-19 and non-COVID-19 publication subsets.

3.2. Steps of the analysis

To better frame our results, first, an overview of international research involving Chinese-affiliated authors was performed. The focus has been on health-related studies, and the results have been based upon general data retrieved from the WoS. In this framework, a descriptive analysis of our database was then performed, from which a few interesting insights about the form of the research networks related to COVID-19 emerged.

The second step involved performing a social network analysis on the sets identified in point 7 of the previous subsection to study their shape and features, focusing on comparisons between the COVID-19 and non-COVID-19 subsets and between China and the U.S.

In all the networks, countries represent nodes, while edges identify the existence of at least one coauthored publication between countries. Furthermore, each edge is weighted using the number of coauthored publications between each pair of countries. By construction, the networks are undirected and ego-centered (on China or on the U.S.). More details on these choices can be found in Appendix 2.

Finally, starting from the results of the network analysis, we looked more in depth into the dynamics of such networks, identifying countries joining or leaving collaborations with China or the U.S. or changing their collaborative behavior with these countries. In particular, we analyzed the intensity of each country's involvement in COVID-19 research and its involvement in other topics in the same scientific field. To do so, we compared the differences between the sets of publications that were either not COVID-19-oriented in 2021 (*2021_TOP5_NoCOV)* or were published in 2018 (*2018_TOP5*) and the set of COVID-19-oriented publications in 2021 (*2021_TOP5_COV)*.

More details about the methodology and the taxonomy can be found in Section 4.3.

4. Results

4.1. Overview of the role of China in international research

Over the 1990–2022 span, China has emerged as one of the core actors in research, as proxied by publications. According to the data available in the Web of Science repository, during this period, researchers based in this country have passed from publishing a few thousand contributions per year (8239 in 1990) to 936,564 in 2022. In three decades, the country has climbed up the rankings of nations with the highest number of publications in international journals, entering the top 10 in the 2000s, reaching the second position since 2010 and ranking first in 2022 (Fig. 1). In particular, the increased role of China as a producer of research is mirrored by a proportional decrease in the weight of the U.S. as a source of publications. A sort of "substitution effect" in the role played by the countries in international research therefore seems to exist, while the weights of the other nations remain virtually constant across the whole period.

Within research publications, a particularly relevant role is played by the health sciences. After 1990, these subjects stably represented approximately 40 % of total publications.[3] If we look both at the absolute number and at the relative weight of this field in worldwide publications, the trends do not seem to be different from those observed for publications in general: we still observe an increase in the publications of Chinese researchers since the 2000s, with a greater speed than that of other areas of the world (Fig. 2a), which is reflected in what seems to be a substitution between Chinese publications and the G8 (mainly U.S.) publications (Fig. 2b).

The data depicted thus far seem to underline the emergence of China as the leading research giant, both in general and within the field of health research. However, the extent to which the international research produced by Chinese authors is also *transnational* (i.e., coproduced through international research collaboration) needs more in-depth analysis.

Some relevant insights emerge, in fact, when examining the degree of international collaboration in which Chinese researchers have engaged in health studies (Fig. 3): while European countries and the U.S. have increased the intensity of international collaboration on these subjects, recognizing the advantages of joint research, China, which was the most open country at the beginning of the period, has progressively reduced the relative number of publications with international partners, ranking last among the considered countries at the end of the period under scrutiny.

4.2. A focus on our database

The methodology described in Section 3.1 allows us to identify different groups of publications for China and the U.S. (see Table 2).

A first glance at the different subsets of the data highlights the prevalence of nationally bounded publications, both for China and for the U.S. Despite an evident difference in terms of size, in more than 70 % of cases, all the authors of the considered publications have a single national affiliation. A difference that seems to emerge between China and the U.S. is a slightly greater tendency of the former toward international coauthored publications when dealing with COVID-19 (27.24 % versus 25.66 %).

When looking at international collaborations within the various subgroups, some interesting results emerge. Overall (Table 3), for both China and the U.S., the number of countries involved in COVID-19 research networks is substantially lower than that involved in non-COVID-19 networks (100 against 141 for China and 154 against 185

[3] Source: authors' elaborations of WoS.

Table 5
Social network analysis statistics – China.

Network name	2018_TOP5	2021_TOP5	2021_TOP5_COV	2021_TOP5_NoCOV
Nodes	153	151	101	142
Edges	6346	4554	1355	4323
Minimum value	0	0	0	0
Maximum value	1100	1603	299	1304
Density/reciprocity	0.5458	0.4021	0.2683	0.4318
Transitivity	0.8467	0.741	0.5677	0.7585
Degree centralization	0.4603	0.6059	0.7465	0.5763
Strength centralization	24.747	43.299	11.958	37.359
Strength centralization by publication	0.0126	0.0120	0.0187	0.0126

Source: Authors' elaboration of WoS data.

Table 6
Social network analysis statistics – USA.

Network name	2018_TOP5	2021_TOP5	2021_TOP5_COV	2021_TOP5_NoCOV
Nodes	178	189	160	186
Edges	7325	6415	2753	6027
Minimum value	0	0	0	0
Maximum value	1431	2062	358	1704
Density/reciprocity	0.4649	0.3611	0.2164	0.3503
Transitivity	0.7957	0.6951	0.5779	0.6973
Degree centralization	0.5411	0.6457	0.7616	0.6568
Strength centralization	87.84	119.05	22.18	101.81
Strength centralization by publication	0.0115	0.0101	0.0127	0.0101

Source: Authors' elaboration of WoS data.

Table 7
Social network analysis statistics – China excluding coauthored publications with the U.S.

Network name	2018_TOP5	2021_TOP5	2021_TOP5_COV	2021_TOP5_NoCOV
Nodes	108	120	85	108
Edges	1799	1270	559	1036
Minimum value	0	0	0	0
Maximum value	205	393	88	317
Density/reciprocity	0.3113	0.1779	0.1566	0.1793
Transitivity	0.7921	0.5728	0.4729	0.5927
Degree centralization	0.7016	0.8361	0.8637	0.8362
Strength centralization	11.942	24.868	6.318	22.623
Strength centralization by publication	0.0138	0.0125	0.0186	0.137

Source: Authors' elaboration of WoS data.

for the U.S.). However, the shrinking of Chinese networks is more pronounced than the U.S., decreasing by 29 % compared with 17 % for the U.S.

At the *individual publication* level (Table 4), COVID-19 publications seem to involve, on average, a slightly larger number of countries. This might suggest that the COVID-19 network revolves around a lower number of countries but with more structured relationships across a larger number of partners per publication. For China, this is more evident given that, compared to pre-COVID coauthored publications, the publications in the top 5 sectors under scrutiny, on average, involved a lower number of countries.

A similar trend emerges when examining the number of authors per publication: while in China, this number has fallen compared to that in the pre-COVID-19 situation, the publications related to COVID-19 involve more researchers on average than non-COVID-19 publications.

4.3. Social network analysis

Having seen these first average results, it seems useful to further deepen the analysis of the COVID-19 and non-COVID-19 networks by

Table 8
Social network analysis statistics – the U.S. excluding coauthored publications with China.

Network name	2018_TOP5	2021_TOP5	2021_TOP5_COV	021_TOP5_NoCOV
Nodes	175	183	149	179
Edges	4569	4671	2371	4006
Minimum value	0	0	0	0
Maximum value	1340	1884	311	1573
Density/reciprocity	00.3001	0.2805	0.2150	0.2515
Transitivity	0.6601	0.6036	0.5662	0.5820
Degree centralization	0.7079	0.7275	0.7956	0.7569
Strength centralization	75.958	104.248	19.297	90.442
Strength centralization by publication	0. 0102	0.0102	0.0133	0.0103

Source: Authors' elaboration of WoS data.

Table 9
Assortativity statistics.

	2018_TOP5	2021_TOP5	2021_TOP5_COV	2021_TOP5_NoCOV
CHINA				
Assortativity coefficient	−0.733	−0.771	−0.657	−0.832
Weighted assortativity	−0.345	−0.273	−0.183	−0.396
Strength assortativity	−0.317	−0.273	−0.265	−0.294
USA				
Assortativity coefficient	−0.715	−0.655	−0.642	−0.637
Weighted assortativity	−0.252	0.085	−0.271	0.067
Strength assortativity	−0.207	−0.212	−0.237	−0.213

Source: Authors' elaboration of WoS data.

Table 10
Assortativity statistics – excluding reciprocal coauthored publications.

	2018_TOP5	2021_TOP5	2021_TOP5_COV	2021_TOP5_NoCOV
CHINA				
Assortativity coefficient	−0.5093	−0.6010	−0.6023	−0.6582
Weighted assortativity	−0.4784	−0.3195	−0.4319	−0.3988
Strength assortativity	−0.2687	−0.2189	−0.2824	−0.2494
USA				
Assortativity coefficient	−0.7731	−0.6478	−0.6364	−0.6289
Weighted assortativity	−0.1508	0.2068	−0.3365	0.2051
Strength assortativity	−0.1959	−0.2029	−0.2436	−0.2010

Source: Authors' elaboration of WoS data.

Table 11
Top 10 country partners with China by number of publications.

2018_TOP5	n	2021_TOP5	n	2021_TOP5_COV	n	2021_TOP5_NoCOV	n
USA	1100	USA	1603	USA	299	USA	1304
Australia	296	England	583	England	133	England	450
England	271	Australia	498	Australia	71	Australia	427
Canada	176	Canada	296	Canada	49	Canada	247
Japan	113	Germany	190	Pakistan	38	Germany	157
Netherlands	105	Pakistan	167	Germany	33	Netherlands	140
Germany	103	Netherlands	165	Malaysia	29	Pakistan	129
Sweden	84	S. Korea	152	Singapore	27	S. Korea	128
France	80	Taiwan	151	Netherlands	25	Taiwan	128
Taiwan	75	Japan	150	S. Korea	24	Japan	128

Source: Authors' elaboration of WoS data.

Table 12
Top 10 country partners with the U.S. by number of publications.

2018_TOP5	n	2021_TOP5	n	2021_TOP5_COV	n	2021_TOP5_NoCOV	n
England	1431	England	2062	England	358	England	1704
China	1095	China	1550	China	294	China	1256
Canada	997	Canada	1331	Canada	205	Canada	1126
Australia	758	Australia	947	Australia	145	Australia	802
South Africa	661	South Africa	810	India	128	South Africa	718
France	526	Germany	726	Italy	124	Germany	616
Germany	519	Switzerland	656	Brazil	115	Switzerland	549
Switzerland	512	Brazil	639	Germany	110	Brazil	524
Brazil	430	India	614	Switzerland	107	Netherlands	507
Netherlands	425	France	583	South Africa	92	France	494

Source: Authors' elaboration of WoS data.

performing social network analysis (SNA), which might provide further information about the differences or similarities between the different subsets.[4]

Tables 5 and 6 show the main results of the SNAs for the various subsets.

Compared with those of the U.S., China's networks generally have a smaller number of nodes and edges, confirming the presence of a smaller and less interconnected publication landscape. Despite a growth in the number of nodes for the U.S. and a substantially stable number of nodes in China, in the TOP5 sectors, both countries showed a decrease in the number of edges from 2018 to 2021. This indicates a tendency toward looser networks in both countries. This tendency is confirmed by the value of the density/reciprocity metric, which represents the proportion of the actual connections to all possible connections in the network. In both cases, 2021 sets had lower densities than did 2018 sets, suggesting some degree of fragmentation in the publication networks. This result is also confirmed by the transitivity measure (i.e., the tendency of nodes to cluster together), which assumes the same interpretation as density in

[4] The analysis is performed while aware of the well-known difficulties in applying statistical testing to comparative social network analysis (Smith, Calder and Browning, 2016), which we try to overcome by matching the SNA with the other descriptive analyses presented in the paper.

Table 13
Partner countries leaving/joining the Chinese/U.S. research network in the TOP5 research areas.

	2018 Partners	2021 Partners	Leavers	Joiners	Others
China	152	150	20	18	132
U.S.	177	188	2	13	175

Source: Authors' elaboration of WoS data.

ego-centered networks (Perry et al., 2018). These fewer partner countries per publication can be partially attributed to lock-down initiatives during the pandemic. As reported by the International Organization for Migration, between March 2020 and the end of 2021, 228 countries have issued some form of entry restrictions (International Organization for Migration, 2023). This has led to a substantial slowdown of international movements of people, and might have impacted negatively on international research networks, in particular for those research areas that require on-field activities for data collection.

However, more information about the shape of these networks can be retrieved from comparisons of degree and strength centralization measures. The first determines how concentrated the connections are around a few high-degree nodes, which on average are more well connected to any other node (i.e., share at least one publication) than the others are. According to this metric, the 2021 U.S. network shows a slightly greater degree of centralization than the 2021 China network. This finding suggested that a smaller subset of nodes in the U.S. network has more connections than does that in China. Strength centralization adds to this information the weight of the connections: in our framework, it measures the extent to which the total number of publications revolves around a limited number of nodes. The 2021 US network exhibits the highest strength centralization, suggesting that a few (top) nodes hold a substantial share of coauthored publications in this network. However, it should be noted that in our case, strength centralization is highly dependent upon the number of publications included in each subset: with a similar degree of centralization, areas of research with a lower number of publications are less likely to have higher strength centralization. We account for this aspect by dividing the strength measure by the total number of publications in the network.

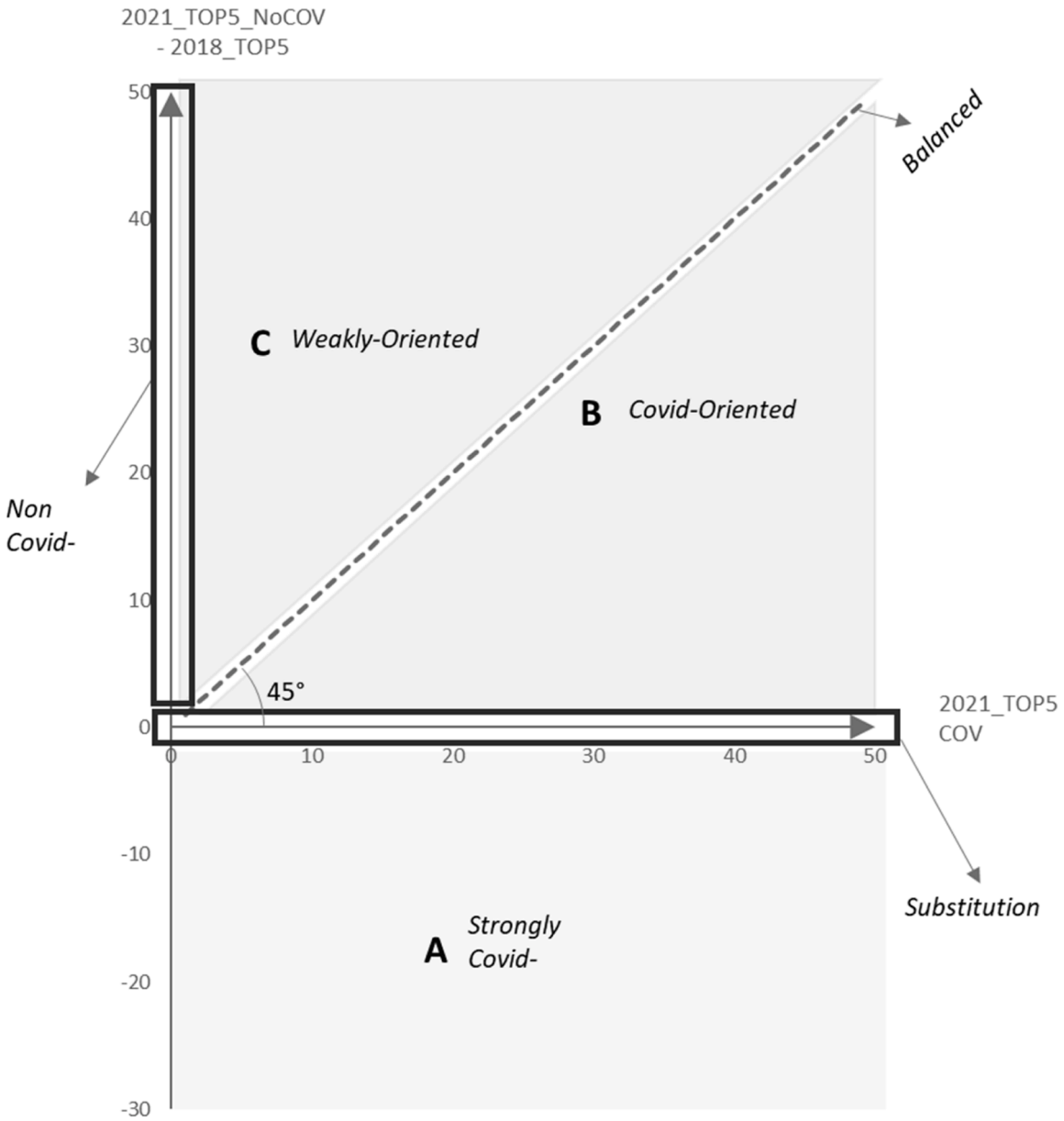

Fig. 4. Taxonomy of the countries according to collaborative behavior in COVID-19- vs. non-COVID-19-related publications.

Table 14
Partners' behaviors in TOP5 research sectors.

		STRONGLY COVID-ORIENTED	COVID-ORIENTED	SUBSTITUTING	BALANCED	WEAKLY COVID-ORIENTED	NON—COVID ORIENTED
China	Number	28	12	14	7	39	50
	Percent	18.67	8.00	9.33	4.67	26.00	33.33
U.S.	Number	24	45	7	15	65	34
	Percent	12.63	23.68	3.68	7.89	34.21	17.89

Source: Authors' elaboration of WoS data.

Table 15
Partners' behaviors in TOP5 research sectors – excluding publications involving China–U.S. relations.

		STRONGLY COVID-ORIENTED	SUBSTITUTING	COVID-ORIENTED	BALANCED	WEAKLY COVID-ORIENTED	NON—COVID ORIENTED
China	Number	20	8	4	8	44	51
	Percent	14.81	5.93	2.96	5.93	32.59	37.78
U.S.	Number	21	7	42	10	67	40
	Percent	11.23	3.74	22.46	5.35	35.83	21.39

Source: Authors' elaboration of WoS data.

Table 16
Pseudotransition tables: From non and/or weakly COVID-19-oriented with China/the U.S. to strongly COVID-19-oriented with the U.S./China.

	Strongly COVID-oriented with the U.S.		Strongly COVID-oriented with China
Non-COVID Oriented with China (50 countries)	9 (18 %)	Non-COVID Oriented with the U.S. (34 countries)	0 (0 %)
Non-COVID Oriented+ Weakly COVID Oriented with China (89 countries)	28 (31 %)	Non-COVID Oriented+ Weakly COVID Oriented with the U.S. (99 countries)	10 (10 %)

Source: Authors' elaboration of WoS data.

Table 17
Pseudotransition tables excluding publications involving China–U.S. relations.

	Strongly COVID-oriented with the U.S.		Strongly COVID-oriented with China
Non-COVID Oriented with China (51 countries)	13 (26 %)	Non-COVID Oriented with the U.S. (40 countries)	0 (0 %)
Non-COVID Oriented+ Weakly COVID Oriented with China (95 countries)	34 (37 %)	Non-COVID Oriented+ Weakly COVID Oriented with the U.S. (108 countries)	8 (7 %)

Source: Authors' elaboration of WoS data.

Delving into our main object of study, the possible impact of COVID-19 on transnational publication networks, the following elements emerge. The COVID-19 networks in both countries had fewer nodes and edges than did their respective 2021_TOP5 networks overall, confirming the descriptive evidence that COVID-19 research publications involve a more limited number of countries in both China and the U.S. Since we are comparing COVID-19 publications with publications in the same research fields, such additional shrinking compared to 2021_TOP5 network cannot be attributed to the impediments to travel and research abroad caused by lockdown policies, which we can assume have had a similar impact on homogeneous research areas.

Furthermore, the density/reciprocity in these networks was lower than that in the overall 2021 networks and the 2021 non-COVID-19 network for both China and the U.S., suggesting that the COVID-19 research network is more fragmented and less connected. The transitivity in the COVID-19 network is relatively high, but its value in both China and the U.S. is notably lower than that in the other networks. Given that transitivity is a vital measure of local clustering patterns, a lower value indicates that COVID-19 research publications are characterized by fewer clustered collaborations than the general research landscape is. The COVID-19 networks instead had the highest values for degree centralization, indicating that a few nodes catalyze a greater proportion of connections, acting as coleaders with China or the U.S. This was confirmed by the degree and strength centralization measures, once considering the structurally lower number of publications focused on COVID-19 with respect to the other sets. In fact, they both show higher numbers than in all the other networks. In other words, if we had to visualize the COVID-19 networks compared to the others, it would look more like a star-shaped network—with China/the U.S. and a few other countries at the core and connected with the other nodes—rather than one in which all the participants take part in the research in a multilateral and balanced way.

In conclusion, this social network analysis highlights the differences between publication networks centered in China and the U.S., as well as the impact of COVID-19 research on these networks. The COVID-19 networks show distinct characteristics in terms of size, connectivity, and centralization. These networks appear, both in China and in the U.S., to be more exclusive and less centralized in connection strengths; additionally, they still exhibit clustering patterns. These findings could be partially a consequence of time. Research on COVID-19 had to be performed rapidly during 2021 to offer solutions for the pandemic in the shortest possible time. This meant that few existing research networks, compared to similar areas of research, could have been structured or reoriented toward COVID-19. At the same time, COVID-19 networks nonetheless seem to be more selective and exclusive with respect to the number of countries involved.

4.3.1. Robustness checks

A major part of Chinese international coauthored publications is made with the U.S. as a noteworthy partner (see also Table 11). In particular, concerning COVID-19-related publications, China shares 299 out of 638 publications in its TOP5 sectors with the U.S., corresponding to 46.87 % of the total. Therefore, when examining the peculiar results obtained in social network analysis of COVID-19 publications, one could suspect that, rather than indicating the specificity of COVID-19 research as such, these results are more driven by the role played by the U.S. in this area of research. To exclude this possibility, we repeated the social network analysis excluding all the publications that the two countries shared in their respective TOP5 sectors. The results are presented in Tables 7 and 8 and are consistent with the main results.

Finally, we analyzed how the assortativity metrics further characterized the networks under consideration (Tables 9 and 10). First, in line with the evidence generally found for egocentric networks (Gupta et al., 2015), we find a strong tendency toward a disassortative nature, i.e., the tendency to collaborate with nonsimilar partners in terms of connections, which is also driven by the structural properties of this specific class of networks. Nevertheless, when disaggregating the 2021 sets of COVID-19 and non-COVID-19 publications for China, we find a smaller tendency toward disassortativity in the COVID-19 network (corresponding to a coefficient with a smaller absolute value). For the U.S., the case is reversed, as the non-COVID-19 network appears to be assortative, coupled with a very disassortative COVID-19 network.

In this case, however, the results are indeed driven by the role that the U.S. plays in the Chinese network: if we calculate once again the statistics excluding the publications with the U.S., the Chinese COVID-19 research network shows a more disassortative nature, implying collaboration between strong and weak actors. This is likely due to the high specificity of COVID-19-related knowledge, and it is also in line with the previously detected higher values of degree centralization.

4.4. A taxonomy of collaborative behaviors

Once the framework related to the shape and density of the overall networks is depicted, it might be worth investigating more deeply the behavior of the single-partner countries involved in research in the selected sectors, whether partnered with China or the U.S. The specific questions we would like to answer are as follows: what are the behaviors of the partner countries of China and the U.S. in the 2021_TOP5 networks? Are these countries more focused on COVID-19-related research? Are they joining those networks mainly to participate in COVID-19 research?

A note is first required in relation to the top 10 national partners in the selected sectors. Concerning China (Table 11), the U.S. was the most frequent partner in all the groups and subgroups under consideration. However, between 2018 and 2021, in the TOP5 sectors, the U.S. seemed to lose some of its centrality to its second partner (Australia in 2018 and England in 2021). This effect was even more pronounced in the COVID-19 set, in which the first-to-second partner ratio was only 2:1. In comparison, no similar trend seems to emerge for the U.S. (Table 12) as the distance between England as the first partner and China as the second partner seems unchanged across all the groups.

To further determine the possible effect of COVID-19-related research on these networks, the first evidence about the dynamics of the research groups can be found in Table 13, which summarizes the number of countries according to whether (a) they were collaborating with China/the U.S. in 2018 but stopped in 2021 (Leavers); (b) they were not collaborating with China/the U.S. in 2018 but started in 2021 (Joiners); and (c) they were collaborating with China/the U.S. in 2018 and continued to do so (others). Although the total number of countries publishing with China has not changed substantially (152 in 2018 vs. 150 in 2021), we observe a relatively large turnover, with 20 leavers and 18 joiners. Conversely, the U.S. has substantially increased their number of partners, from 177 to 188. However, in terms of the number of publications, China's leavers and joiners are countries with a relatively low output: against a total average of 23.9 publications per country in 2018 and 45.12 publications in 2021, these two groups of leavers and joiners collaborate on average in 1.75 publications (leavers) and in 2.61 publications (joiners). From this point of view, therefore, China's networks seem to show greater volatility, particularly with respect to relations that might appear more peripheral (i.e., smaller in number). This seems to point to the difficulty of the Chinese research system to serve as a stable catalyst in this research field, particularly for marginal collaborators.

To further explore these aspects, we sketch the behaviors of the partner countries in the 2021 network. In particular, the aim is to understand whether COVID-19 publications have had a significant role in the involvement of research groups coming from partner countries in the Chinese/U.S. network, or if the contributions of this research area have been marginal. To do so, we analyzed the relationships among the three variables:

1. The number of 2018 coauthored publications with China/the U.S. in TOP5 sectors;
2. The number of 2021 coauthored publications with China/the U.S. in TOP5 sectors related to COVID-19;
3. The number of 2021 coauthored publications with China/the U.S. in TOP5 sectors unrelated to COVID-19.

We calculated the difference between Variables (3) and (1) and then compared the obtained measure with Variable (2). In this way, we obtained a taxonomy of the different collaborating behaviors.

We can read the taxonomy through the theoretical graphical representation presented in Fig. 4, in which the x-axis represents the number of 2021 COVID-19 publications and the y-axis is the difference between 2021 non-COVID-19 publications and 2018 publications in the TOP5 sectors. Starting from the lower quadrant of the graph, we find:

a) Strongly COVID-oriented countries (A area): Countries that published mainly coauthored COVID-19-related research and that decreased the amount of coauthored non-COVID-19 research from that in 2018. Mathematically, these are the countries for which the difference between 2021 non-COVID-19 publications and 2018 publications was negative, while they had COVID-19 coauthored publications.
b) Substitution (x-axis): In these countries, the number of 2021 non-COVID-19 publications is the same as that in the 2018 top 5 publication areas, and they also have a positive number of COVID-19-related publications. We define these as 'substituting' because any additional publication made by these partners compared to the publications in 2018 focused on COVID-19 research.

Source: Authors' elaboration of WoS data

a) COVID-oriented countries (B area): This group exhibited a positive difference between the 2021 non-COVID-19 publications and the 2018 publications. However, the number was lower than the number of COVID-19-related publications.
b) Balanced countries (bisector): These countries have seen growth in the number of non-COVID-19-related publications in the top 5 sectors compared to the total in 2018, and this growth is numerically equivalent to the number of COVID-19 publications. The growth of the intensity of the relationship between these countries and China/the U.S. has been equally distributed between COVID-19-related and non-COVID-19-related research.
c) Weakly COVID-oriented countries (C area): These countries have a limited interest in publishing in the COVID-19-related area; while they still publish articles related to COVID-19, the number of articles is lower than the growth in 2021 non-COVID-19 publications from the number of 2018 publications.
d) Non-COVID-oriented countries (y-axis): The research groups of these countries, while continuing to collaborate with China/the U.S. in the TOP5 sectors in 2021 as they did in 2018, chose to do so only on non-COVID-19 topics; in other words, the number of COVID-19-related publications was zero, while the difference between 2021 and 2018 was positive.

We report the results of this taxonomy in Table 14.

Interestingly, most partners, both of China and the U.S., are weakly or not involved in COVID-19-related research. However, apart from this

commonality, all the other figures seem to indicate that, compared to the U.S., the Chinese network has been less able to attract international researchers to COVID-19-related research compared to other topics in the health sciences fields.

The most relevant figure is related to the COVID-19-oriented group of countries: it represents almost 24 % of total partners with the U.S. and only 8 % of those with China. Even if the number of strongly COVID-19-oriented partners is greater for China, if we also include the COVID-19-oriented category, the Chinese network is less attractive than the U.S. network is (26.67 % for China, against more than 36 % for the U.S.).

This interpretation is even reinforced when we analyze the networks excluding the publications involving China–U.S. relations (Table 15).

Is the weak engagement of China's foreign partners in COVID-19 research the result of the scarce interest of these specific countries in COVID-19-related research in general, or is it more specifically related to a weak attractiveness in collaborating on such topics with China?

To address this point, we constructed a pseudotransition table representing the extent to which countries that were either not or weakly oriented toward COVID-19 research with China are instead strongly engaged in COVID-19 research with the U.S. The results, presented in Table 16 for the whole sample and in Table 17 excluding publications involving China–U.S. relations, provide quite a clear picture of this point.

The answer seems to show that there is not a scarce propensity for or possibility of collaborating on COVID-19 research in general but rather of collaborating on the topic *with China*: 18 % of the countries that do not have any shared COVID-19 publications with Chinese authors are actually strongly engaged in COVID-19 research with the U.S., and this number increases to 31 % if we also include those countries with a weak orientation toward COVID-19-related coauthored publications with China. The result is even stronger when we exclude from the analysis the publications where China and the U.S. are coauthors: the figures increase to 26 % in the first case and to 37 % in the second. This might indicate that in the coauthored publications where the two countries are present, other actors join more because of the presence of the U.S. in the network, rather than because of an interest in conducting research with Chinese scholars.

Finally, it must be highlighted that this trend is not bilateral: when we look at the countries not oriented toward collaborating on COVID-19 with the U.S., we find that none of them have strong COVID-19-related collaboration with China, and the transition also remains very limited, including the countries that are weakly COVID-19-oriented in the U.S. network.

5. Conclusions and policy implications

In the "Medium-to-Long-Term Plan for the Development of Science and Technology", the Chinese government declared the intention to transform the country into a world leader in science and technology by 2050 (Cao et al., 2006, 2020). In line with this aim, in the past few decades, China has been massively investing in surpassing the U.S. as a technological leader worldwide (Sharif, 2015). This is done not only by counting on the wide national market but also by assuming a leadership position in international research and steadily increasing R&D expenditures. These investments in R&D are already higher than those of Japan and Germany in terms of contributions to global funding; they have also reached the investment levels of the EU and are rapidly closing the gap with those of the U.S. (Crane, 2023; Veugelers, 2017). China has recently become the leader in several key technologies, such as advanced explosives, nanomaterials and drone technology, and can produce research that has a much greater impact than that of the U.S. (Knott, 2023; Hurst, 2023). However, there are also several studies analyzing China's scientific system and pointing to its weaknesses and frailties. Horta and Shen (2019) show that the weight of Chinese publications in international journals is mitigated by the specialization in specific fields (typical of developing countries), while neglecting other areas. Furthermore, there seems to have been an excessive attention towards quantity to the detriment of quality, also due to the incentives given to researchers to enhance the number of international publications (Di Tommaso et al., 2020). The government itself is now increasingly aware of the situation and is trying to redirect its scientific system toward more valuable research in terms of quality, for example by abolishing cash rewards to researchers for their publications (Mallapaty, 2020).

The analysis carried out in this paper aimed to identify possible peculiarities in COVID-19 research networks. Confronting the characteristics of China and the U.S. has emphasized the presence of national specificities, while comparisons with non-COVID-19 research in the same fields has allowed us to identify some peculiar traits of these networks. As expected, all the Chinese networks and subsets are smaller than the U.S. networks, both in terms of edges and nodes. Despite the increasing presence of China in international research and the overtaking of the U.S. in terms of relative weight in transnational publications, in the sectors under scrutiny, China's international research system still appears to be smaller in size and less interconnected.

In both countries, the COVID-19 network is more fragmented and less connected, involving fewer countries than the non-COVID-19 network. Moreover, the non-COVID-19 network sees the presence of nodes that catalyze a relatively greater number of relations. Despite the worldwide impact of the pandemic pushing towards a higher degree of collaboration among different countries (Jit et al., 2021) and an increased willingness to propose a unified approach to finding a solution to such an impactful common problem, our results point towards the prevalence of closure forces. Even if, as already mentioned, some review studies found an initially increased propensity toward international collaboration on COVID-19 research, the relative fragility of COVID-19 networks identified by our research shows that in the long run, different forces might prevail, discouraging the increase in TRNs. As highlighted in Section 2, these might have been national economic interests related to the development of vaccines or to the provision of therapies and to the supply of medical devices (van Oorschot et al., 2023); similarly, other factors could have contributed to this finding, such as the need to maintain secrecy over strategic findings, the political tensions between states that reduced their levels of trust, and specific policy approaches toward self-sufficiency/cooperation in emergencies.

Specifically, regarding the role played by China in the COVID-19-related research network, our results seem to point neatly toward a lower capacity of the Chinese research system to catalyze interest from international scientists to study COVID-19-related issues than that of the U.S. system. Despite being the country where the pandemic originated, China has been less engaged in international research dealing with COVID-19 than in other explorations of specific topics in the same scientific sectors. This cannot be said of the U.S. research system, which has proven to be able to stably and strongly attract (and coordinate) international scholars eager to engage in COVID-19-related research. This shows that there is not a scarce interest in COVID-19-related coauthored publications in general but rather a relatively low propensity or possibility of collaborating on the topic *with China*. This might be due to two trends: (1) a lower availability of other countries to collaborate with China or (2) an increasing inwardness of the Chinese scientific system. As regards the first, the diffidence towards China has been increased in recent years by the polemics about unfair practices (such as a misuse of intellectual property coming from foreign partners) or the refusal to grant full access to data and information (Ekrem, 2020). Such a diffidence has been with no doubts nurtured during the pandemic period. The WHO (World Health Organization) has more than once accused China of hiding relevant data about the origin and the diffusion of the virus (see, among others, Cohen, 2023; Mancini, 2023; The Associated Press, 2020). Others have highlighted possible manipulations of data about origin and the diffusion of the disease in China (Calhoun, 2022; Yang et al., 2021; McMorrow and Liu, 2023). Whether the allegations are true or not, the fact remains that they have contributed to an

international climate of distrust that may have easily spilled over into the realm of scientific research.

Regarding, instead, the growing closure of the Chinese research system (Petti, 2022), very recently Owens (2023) has underlined the increasing tendency of Chinese researchers to publish on their own. If this might be a consequence of the pandemic, it is however a tendency that started before the outbreak of COVID-19: "In 2022, China's Share/Count ratio reached 82 % (a ratio of 100 % would indicate no international collaboration at all). This number has been rising steadily for several years: in 2015, China's ratio was 72 %, for instance. At the same time, the ratio for most other major science nations has been falling. For example, the US ratio was 75 % in 2015 and 70 % in 2022, and for Germany, the ratio fell from 56 % to 50 % over the same period. In some scientific journals and fields, the trend is even more pronounced" (Owens, 2023). The number of co-authored papers has increased, but it has not kept the pace with the number of articles authored only by Chinese, which grew at a higher speed. A role in this trend might also have been played by the geo-political tensions that were already in place before 2020, but which exacerbated during the pandemic period (Owens, 2023).

Furthermore, China has been the country with the longest lockdown. While this prolonged closure may have had a negative effect on all international scientific collaborations in general, the difficulty of conducting face-to-face meetings may have weighed more heavily on COVID-19 research, because of the strategic nature and importance of the topic at hand.

With the currently available data, it is not possible to understand whether this is due to a lower level of international interest (or an increasing diffidence) in collaborating with China or to a lower propensity of the country to work together transnationally on this topic. For this reason, further research is needed to relate these results to relevant aspects, such as specific policy measures, the degree of stability of existing relationships, the role of trust, and the weight of national interventions on the choices of individual researchers.

This, indeed, is not a secondary issue. It is widely acknowledged that international research partnerships allow cross-fertilization of knowledge that may bring to the development of unprecedented results, leading to an acceleration of the global innovation competitiveness and an enhancement of the overall well-being (Aarons et al., 2019; Chen et al., 2019, only to cite some). In this picture, the degree of closure or openness to international collaborations of one of the currently leading players in the scientific community becomes crucial for the future scenario. A scenario in which China is proposing itself as a global player not only in the science and technology field in general but also specifically in the health-related sector (Petti et al., 2020). This is proven by the increasing importance that the Health Silk Road (HSR) acquired in the framework of the Belt and Road Initiative (BRI) just after the COVID-19 outbreak (Huang, 2022). The HSR has passed from being an infrastructure project of the BRI to "an emerging diplomatic initiative for promoting health cooperation in a world increasingly threatened by proliferating public health emergencies" (Cao, 2020), and it is seen as particularly important for developing countries.

In this framework, it is important to continue to study the role of China within international research networks, given that this role is likely to become central not only for the scientific capacity of the country but also for the implications that this will have on other countries. For this reason, continuing to emphasize the importance of policies aimed at favoring international collaborations to facilitate joint efforts to address globally relevant issues is highly relevant.

In examining global collaboration networks amid the COVID-19 pandemic, it is crucial to acknowledge certain limitations inherent in our study, given the type of data we use and the phenomenon we analyze. Such limitations can also provide insights for future researches.

Firstly, this study takes the structures of networks at their current state and it aims to grasp their reactions to the Covid advent, as an event possibly spurring the need for increased collaboration. In this, we have been able to see that the "weaker" Chinese network seems less capable to react in the context of global collaborations. However, while highlighting the evidences related to changes in the structure of the networks, this study does not establish specific causal insights. Indeed, in order to correctly disentangle the underlying data generating process, a long-term or a more granular perspective would be preferrable. For example, future studies might focus on specific field-dynamics, country case studies, or changes in groups of researchers along time.

As an additional warning on the interpretation of our results, we need to keep in mind that the constructed networks are egocentric, given that our data served the purpose of analyzing Chinese network dynamics *vis a vis* the U.S. one. Covering the vast majority of global publications in the studied period, our analysis represents a good proxy of the general trends of COVID-19 publications worldwide. However, there might be additional effects on those networks not involving either China or the U.S. that are not covered by our results.

Finally, this study has compared two static situations, i.e. the networks before and after the COVID-19 spur. It will be interesting in the future to assess whether the closure effects that we have observed in this context will also emerge in the future in the Chinese scientific network as a whole.

CRediT authorship contribution statement

Lauretta Rubini: Conceptualization, Writing – original draft, Writing – review & editing, Supervision, Data curation, Funding acquisition. **Chiara Pollio:** Methodology, Writing – original draft, Writing – review & editing, Visualization, Data curation. **Elisa Barbieri:** Conceptualization, Writing – original draft, Funding acquisition. **Sebastiano Cattaruzzo:** Formal analysis, Writing – original draft.

Data availability

Data will be made available on request.

Funding statement

This article was developed within the project funded by Next Generation EU - "GRINS - Growing Resilient, INclusive and Sustainable" project (PE0000018), National Recovery and Resilience Plan (NRRP) – PE9 - Mission 4, C2, Intervention 1.3″. The views and opinions expressed are only those of the authors and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

This research was also conducted within the framework of the project 'Emilia-Romagna International School of Policy' (CUP: E45J19000150004) funded by Emilia-Romagna regional government.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.strueco.2023.12.018.

Appendix 1 – Health-related sectors

Health-related sectors have been considered including in the analysis the following Web of Science categories:

- ALLERGY
- ANATOMY MORPHOLOGY
- ANDROLOGY
- ANESTHESIOLOGY
- AUDIOLOGY SPEECH LANGUAGE PATHOLOGY
- BIOCHEMICAL RESEARCH METHODS
- BIOCHEMISTRY MOLECULAR BIOLOGY
- BIOLOGY
- BIOPHYSICS
- BIOTECHNOLOGY APPLIED MICROBIOLOGY
- CARDIAC CARDIOVASCULAR SYSTEMS
- CELL BIOLOGY
- CELL TISSUE ENGINEERING
- CHEMISTRY MEDICINAL
- CLINICAL NEUROLOGY
- CRITICAL CARE MEDICINE
- DENTISTRY ORAL SURGERY MEDICINE
- DERMATOLOGY
- DEVELOPMENTAL BIOLOGY
- EMERGENCY MEDICINE
- ENDOCRINOLOGY METABOLISM
- ENGINEERING BIOMEDICAL
- EVOLUTIONARY BIOLOGY
- GASTROENTEROLOGY HEPATOLOGY
- GENETICS HEREDITY
- GERIATRICS GERONTOLOGY
- GERONTOLOGY
- HEALTH CARE SCIENCES SERVICES
- HEALTH POLICY SERVICES
- HEMATOLOGY
- IMMUNOLOGY
- INFECTIOUS DISEASES
- INTEGRATIVE COMPLEMENTARY MEDICINE
- MATERIALS SCIENCE, BIOMATERIALS
- MEDICAL ETHICS
- MEDICAL INFORMATICS
- MEDICAL LABORATORY TECHNOLOGY
- MEDICINE GENERAL INTERNAL
- MEDICINE LEGAL
- MEDICINE RESEARCH EXPERIMENTAL
- MICROBIOLOGY
- MYCOLOGY
- NEUROIMAGING
- NEUROSCIENCES
- NURSING
- NUTRITION DIETETICS
- OBSTETRICS GYNECOLOGY
- ONCOLOGY
- OPHTHALMOLOGY
- ORTHOPEDICS
- OTORHINOLARYNGOLOGY
- PARASITOLOGY
- PATHOLOGY
- PEDIATRICS
- PERIPHERAL VASCULAR DISEASE
- PHARMACOLOGY PHARMACY
- PHYSIOLOGY
- PRIMARY HEALTHCARE
- PSYCHIATRY
- PSYCHOLOGY
- PSYCHOLOGY APPLIED
- PSYCHOLOGY BIOLOGICAL

- PSYCHOLOGY CLINICAL
- PSYCHOLOGY DEVELOPMENTAL
- PSYCHOLOGY EDUCATIONAL
- PSYCHOLOGY EXPERIMENTAL
- PSYCHOLOGY MATHEMATICAL
- PSYCHOLOGY MULTIDISCIPLINARY
- PSYCHOLOGY PSYCHOANALYSIS
- PSYCHOLOGY SOCIAL
- PUBLIC ENVIRONMENTAL OCCUPATIONAL HEALTH
- RADIOLOGY NUCLEAR MEDICINE MEDICAL IMAGING
- REHABILITATION
- REPRODUCTIVE BIOLOGY
- RESPIRATORY SYSTEM
- RHEUMATOLOGY
- SOCIAL SCIENCES BIOMEDICAL
- SUBSTANCE ABUSE
- SURGERY
- TOXICOLOGY
- TRANSPLANTATION
- TROPICAL MEDICINE
- UROLOGY NEPHROLOGY
- VETERINARY SCIENCES
- VIROLOGY

Appendix 2 – Technical details on the SNA

Our social network analysis is run on 12 weighted undirected graphs $G_i(N, A, W)$ with $i = 1, 2, \ldots, 12$ that describe networks composed of a set of nodes, $N = n_1,\ n_2, \ldots, n_N$; a set of edges, $A = a_1,\ a_2, \ldots, a_A$; and a set of weights, $W = w_1,\ w_2, \ldots, w_W$, attached to the edges. Each network can be represented in the form of an adjacency matrix M, which in its rows and columns reports the countries participating in the network. Each cell is weighted by the number of coauthored publications connecting the two countries; thus, $m_{ij} = 0$ if country pair $i \in N$ does not coauthor with $j \in N$, while $m_{ij} > 0$ otherwise.

During the analysis, we will rely mainly on the following network-specific statistics:

- Density (which in the case of egocentric undirected networks equals reciprocity), transitivity, degree and strength centralization, and assortativity. Given the considerable number of different approaches that have emerged in the SNA literature, we thereby define the specific indices that we consider. Starting from the most trivial one, density is simply the ratio between the fraction of edges that exist in a network and their total potential number. Then, transitivity consists of the fraction of transitive triplets out of all potential triplets, where a triplet can be any set of three nodes. Basically, this measure quantifies the tendency of nodes with a common neighbor to be connected to each other and is a useful proxy for local clustering phenomena.

Switching our attention to centralization measures, in this study, we employ two of them. A "binary" model, which overlooks the weights associated with the edges, and a more complete model, which also considers the weighted nature of the network. Specifically, following Freeman (2002), we let G be a graph with n nodes; the degree centralization is given by the following:

$$Deg_{centr} = \frac{\sum(k_{max} - k_i)}{(n-1)}$$

where k_{max} is the maximum degree in the network and k_i is the node-level degree. Similarly, for strength centralization, we develop the indicator as follows:

$$Str_{centr} = \frac{\sum(W_{max} - S_i)}{(n-1)(n-2)W_{max}}$$

where W_{max} is the maximum edge strength in the network and S_i is the node-level strength.

Finally, we also exploit the potential of the indices developed by Fagiolo et al. (2010) to measure assortativity phenomena. These, also known as assortative mixing, proxy for the tendency of nodes in a network to connect with nodes that have similar attributes or characteristics. It quantifies the level of homophily or preference for similar connections among nodes in the network. Here, we focus on the patterns of connections (edges) in the network. By measuring this phenomenon, we can gain insights into whether nodes with similar attributes tend to form connections with each other or whether the connections are more random. The three indicators used to measure assortativity are the following: a "simple" assortativity coefficient, which measures the correlation between the number of connections between each node and its neighbors and the average number of connections of the neighbors; the strength assortativity coefficient, which measures the correlation between the number of publications in which each node participates (the node strength) and the average number of publications in which its neighbor participates; and the weighted assortativity, i.e., the assortativity weighted by strength.

A very final note informs the reader that all employed metrics range from 0 to 1, except for the assortativity ones, whose correlations range from -1 to 1, and strength centralization, which depends on the distribution of the weights.

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