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

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Abstract

Research networks play a pivotal role 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 to nurture innovation in R&D intensive companies. Therefore, they are crucial to favor the catching up of countries in the knowledge economy.

In this context, China's experience is particularly relevant because the country has invested heavily in knowledge and this can be argued to be one of the most important structural changes at the global level in the last 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 the research collaboration, in particular with other countries, can become strategic. In this work, we analyze whether the COVID-19 and related research has 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 towards larger and more intensive collaborations internationally or whether closure approaches have prevailed. With respect to China, this also means to understand whether COVID-19 as a global phenomenon has exerted an effect in promoting China as an international research leader or not. In order to do so, we build an original dataset of international co-publication involving China or the U.S. in selected health research fields. Our analysis first shows that COVID-19 research has assumed specific features with respect to other topics in the same research field, shaping research networks in a peculiar way both for 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 network, as it has attracted a relatively lower and more volatile number of countries.

1. Introduction

A growing body of literature looks at research networks as an indicator of larger collaboration networks fostering knowledge spread and innovation in the context of production (Sonnenwald, 2007; Adams, 2013; Di Cagno et al., 2014; Adam &b 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 in different countries. Consistently with the potential of such networks to generate and diffuse innovation, the policies aiming 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" (Adam & Loach, 2015, p. S58).

Frontier research, especially in natural sciences, tends to cluster around specific transnational research networks (hereafter TRNs), which in addition also gather the collaboration of big R&D intensive multinational companies (Nature, 2015). TRNs become, in this framework, an important infrastructure potentially nurturing innovation in big R&D intensive transnational companies. Therefore, being inside or outside such networks seems crucial for countries aiming at catching-up in the "knowledge economy". Further, as noted in Lundvall & Rikap (2022) and previously in Freeman (2002), technological and knowledge revolutions are capstone means of changes in world economic leadership, which are intrinsically temporal phenomena, and in this, the ability to set up an efficient and extensive research network is certainly of utmost importance. To the point that some countries have attempted building their catching-up strategies, by targeting precisely transnational research networks (Rikap and Flacher, 2020).

In this context, the experience of China's catching up is particularly relevant because of its speed, characteristics and of its implications for the world economy (Xie and Freeman, 2019; Freeman, 2002; Lundvall & Rikap, 2022; Di Tommaso et al., 2013; Di Tommaso et al., 2020). In particular, as pointed out by Xie and Freeman (2019), China has invested heavily in the achievement of a comparative advantage in knowledge and this can be argued to be one of the most important structural changes at the global level in the last 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 knowledge, research, and production areas in which international collaboration can indeed assume a strategic role (Ellemers, 2021). In this work, we look at the role that COVID-19 pandemic has played in affecting transnational collaborations in the field of health. Given that it has been an unprecedent event in recent history of global health, what we would expect is a higher tendency of countries towards a coordination of scientific efforts, in order to collectively achieve outcomes that it would otherwise be impossible to reach individually (Jit et al., 2021). The first available studies on this aspect reach contrasting conclusions. If, on one side, some authors have indeed identified an increasing propensity towards international collaboration especially immediately after the outbreak of the pandemic (Lee and Haupt, 2021; Duan and Xia, 2021), others have signaled a wide heterogeneity in national behaviors, with a general tendency in the longer run towards a decrease in collaborations (Abramo et al., 2022).

Our analysis will focus on the case of China. The country is particularly interesting in this regard not only because it is the place in which the virus originated and can therefore represent a particularly significant case study when dealing with COVID-19, but also because it is placing itself as an emerging player in the field of international research.

We analyze whether the COVID-19 and related research has 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 towards larger and more intensive collaborations internationally or whether closure approaches have prevailed. With respect to China, this also means to understand whether COVID-19 as a global phenomenon has exerted an effect in promoting China as an international research leader or not.

We focus on the different degrees of participation of countries in the two networks, before and after the pandemics. In order to do so, we build an original dataset of international co-publication involving China or the U.S. in selected health research fields. The two countries are the major global players in the scientific research, and also engaged in the highest number of joint research on the topic (Lee and Haupt, 2021).

Our analysis first shows that COVID-19 research has assumed specific features with respect to other topics in the same research field, shaping research networks in a peculiar way both for 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 network, as it has attracted a relatively lower and more volatile number of countries.

The contribution of this paper is threefold.

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

Second, more in general, the results of this analysis can spread light on which tendencies might be in place in international collaborations when they are hit by unexpected systemic shocks, and on the capacity of the global system to face them in an open and collaborative way, rather than with a close and diffident attitude. This becomes particularly crucial in the current era, in which societies are confronted with high uncertainty related to global political instability, climate change, and increasing likelihood to have to face similar situations in the future (Marani et al., 2021; Haileamlak, 2022).

Finally, given the aim of China to become a technological leader by 2050, the 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: next paragraph introduces the relevant literature debate on research networks and their linkage with innovation and production, as well as reporting the debate about 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, that are treated in section 4 together with some robustness checks. Section 5 concludes with final remarks, policy implications and implications for future research.

2. Literature review

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

In this, COVID-19, as previous health emergencies, spurred an unprecedented increase in pandemic-related publications, especially but not only in the science and health fields that played a key role also in the development of solutions to overcome it (Zhang et al., 2020; Fry et al., 2020). More in detail, a great deal of scientific contributions has been written (and published) either in the early phases of the pandemic or with it still undergoing (2019-2021), while fewer authors have been engaged in *ex-post* appraisals.

Starting from the quasi-live chronicle of the pandemic, Aviv-Reuven and Rosenfeld (2021) highlight how the pandemic induced less international collaboration and faster publication time for COVID-related papers, partially at the expense of non-COVID ones. The closure in transnational co-authorships is confirmed also by Cai et al. (2021), who underline how in this context, fewer nations and smaller teams have been involved. This latter fact is also verified by Cunningham et al. (2021). Cai et al. (2021) also highlight a time alignment between publication intensity and COVID-19 incidence on the country. This fact is in line with findings by 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 specifically Greek publications suggest that in some cases the pandemic increased transnational collaboration. Also, Duan and Xia (2021) confirm this, despite a considerable regionalization of research, following a clear core-periphery structure. Finally, Gao et al. (2021) study the possible long-term effects, establishing that it did not structurally increase the amount of time spent on research, while it decreased the likelihood of pursuing new research projects.

Switching to *ex-post* evaluations, Carvalho et al. (2023) suggest that the pandemic event induced the academic community to reduce traditional power disparities promoting more scientific globalism. Such a finding is also partially confirmed by Xu et al. (2023), who found that the pandemic induced more collaboration between star scientists and newcomers, which eventually reduces collaboration disparity. Carvalho et al. (2023) also stress the relevance of countries such as USA, China, Great Britain, and India in COVID-related publications, with India having an especially prominent role in vaccine-related research (Zhao et al., 2022). To account for the existing heterogeneity in COVID-related collaboration patterns, Abramo et al. (2022) show that overall, the pandemic significantly spurred national collaborations, while international ones are subject to important variations among countries.

A final note regards how the knowledge base evolved with the pandemic. Zhang et al. (2021) find that some COVID-related research lines returned to basic research pursued way earlier, while some others undertook new paths. Zhang et al. (2023) further elaborate on the phenomenon studying the patterns of referencing and finds 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 compared to similar fields of research, since there has been a common global interest in fighting the pandemic (Duan & Xia, 2021). On the other hand, competitive and selective approaches to the research might have spur from: the necessity to involve specific knowledge and

competencies in the field owned by a selected number of actors; the competition for developing, producing, and commercializing vaccines; different policy approaches to the management of the pandemics and its effects (Fry et al., 2020).

This said, recent research has highlighted the importance of understanding the long-lasting effects of COVID on China, pointing out the structural changes that can be observed within China's economy due to COVID. Han (2022) in particular, underlines a growth of scientific research and information transmission to the detriment of other sectors such as petroleum and finance. Scientific collaborations and information transmission grow thanks to their significantly improved capacity to pull the development of upstream and downstream connected sectors. Researchers conclude in favor for policies supporting scientific research and information transmission as potential long-term drivers of Chinese growth.

In this framework it is important to understand whether COVID has significantly changed the pattern of international scientific collaborations of China. The country represents a particularly interesting case study in this field, given that contrasting forces might be in place. First, being the place from which the virus has originally spread, might have attracted a larger international interest to collaborate with the country, in order to study the origins of the pandemics and find out possible treatments. Second, China is undoubtedly an emerging actor in transnational research networks in general, also in the health fields. The increasing international scientific role of the country might also have brought a larger interest of China for international collaboration. In contrast, the country has applied a unique policy mix to fight COVID-19, using lockdown and Zero-COVID measures most massively and showing a different attitude towards vaccines[1]. This might have instead reduced the propensity of scientists towards international collaboration in this field. Our study aims at shedding some light on the possible results of these contrasting forces.

3. Methodology

Our research aim is to analyze the COVID-19 effects on Chinese health research networks, using the U.S. as a comparison case. To do so, we choose co-publications as a proxy of research collaborations. While some doubts are risen regarding the opportunity to use them to investigate the quality of research (Schmoch and Schubert, 2007), co-authorship is one of the most utilized indicators in the literature to investigate the mechanisms that shape the scientific community, increasingly oriented towards collaborative paths (Kumar, 2015). In our framework of analysis, a transnational research network involving China/the U.S. consists in a group of co-publications (nets) in which there is at least one author with a Chinese/U.S. affiliation and at least another one with a foreign affiliation.

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

Various international repositories collect information about co-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 have built up an original dataset of international co-publications involving China or the U.S. in selected health research fields.

We have adopted a perspective which is both *inter-temporal* and *inter-sectoral*: on one hand, we compare the research networks *before* (selecting 2018 data) and *after* the COVID-19 outbreak (selecting 2021 data)[2]; 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.

To follow this path, the data collection has included several steps that are thoroughly described in the following section.

3.1. Building the database

The procedure used for building both China's and the U.S.' database is the following:

1. Identification of all the publications in WoS with at least one author with a Chinese/US affiliation in health-related scientific fields in 2021. The Web of Science Categories included in the health sector are listed in appendix 1.
2. In order to select the health research fields that were more involved in COVID-19 research, all COVID-19 related publications in health studies have been identified through an iterative keywords search. More precisely, first the most common keywords related to COVID-19 used by the authors were identified, then progressively enlarged with a snowball technique (including abbreviations and synonyms). The search has been performed both in the keywords field and in the title, to be sure to include the highest number possible of COVID-related research.
3. The first 5 health-related sectors according to the incidence of publications on COVID-19 in 2021 (TOP 5) have then been selected for China and the U.S. (table 1). While these sectors are by construction different between the two countries, for both COVID-19 related publications represent between 14% and 20% of total publications in the TOP 5 research areas.

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	3,109	618	19.88%
	Health Policy Services	926	173	18.68%
	Virology	1,582	284	17.95%
	Public Environmental Occupational Health	7,390	1,170	15.83%
	Psychology Clinical	599	84	14.02%

[2] COVID-19 was officially recognized a pandemic in March 2020. Therefore, using 2020 as reference year would have distorted our results, downward biasing the intensity at which international research networks have started focussing on the disease. On the other hand, choosing 2022 would have resulted in missing the peak of COVID-19 related research. According to the Web of Science database, in fact, the number of publications on COVID-19 has been around 86,000 in 2020, almost 148,000 in 2021 and about 126,000 in 2022.

	US			
	Virology	3,155	631	20.00%
	Infectious Diseases	9,983	1,944	19.47%
TOP 5	Primary Health Care	1,055	175	16.59%
	Medical Informatics	3,524	553	15.69%
	Public Environmental Occupational Health	26,695	3,680	13.79%

Source: authors' elaboration on WoS data.

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

3.2. Steps of the analysis

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

The second step has been to perform a social network analysis on the nets identified in point 7 of the previous paragraph to study their shape and features, focusing on the comparison between COVID-19 and non-COVID-19 networks, and China and the U.S..

In all the networks, countries represent the nodes, while the edges identify the existence of at least one co-authored publication between the countries. Further, each edge is weighed using the number of co-authored 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 the appendix 2.

Finally, starting from the results of the network analysis, we have looked more in depth in the dynamics of such networks, identifying countries joining or leaving collaborations with China/the U.S. or changing their collaborative behavior with these countries. In particular, we have analysed the intensity of each country's involvement in COVID-19 research with their involvement in other

topics in the same scientific fields. To do so, we have compared the difference between the publications non-COVID oriented in 2021(*2021_TOP5_NoCOV)* and the publications in 2018 (*2018_TOP5*) with the COVID-oriented publications in 2021 (*2021_TOP5_COV).*

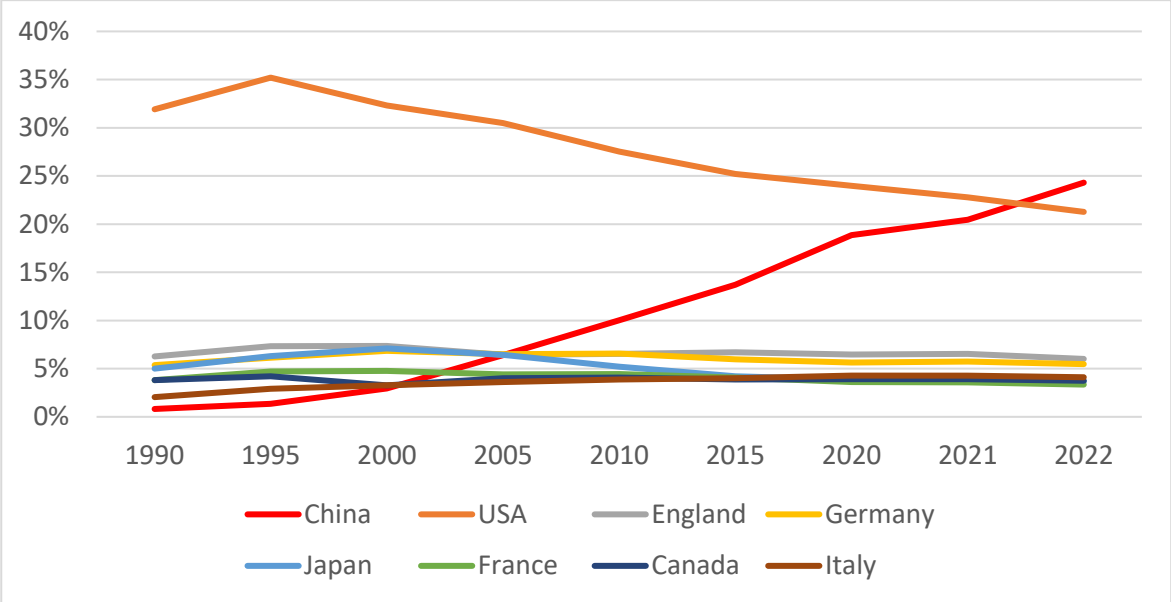
More detail about the methodology and the taxonomy can be found in section 4.3.

4. Results

4.1. Overview of the role of China in international research

Over the 1990-2022 years span, China has emerged as one of the core actors in research, proxied by publications. According to the data available in Web of Science repository, n this period, researchers based in this country have passed from publishing few thousands of contributes per year (8239 in 1990) to 936,564 in 2022. In three decades, the country has climbed up the ranking for number of publications in international journal, entering the top-10 in 2000s, reaching the second position since 2010 and ranking first in 2022 (figure 1). In particular, the increase in the role of China is mirrored by a proportional decrease in the weight of U.S. publications. A sort of "substitution effect" in the role played by the countries in the international research scenario seems therefore to exist among the two countries, while the weight of the others remains virtually constant across the whole period.

Fig. 1 – Weight of selected nations on total publication in international journals



Source: authors' elaborations on WoS data.

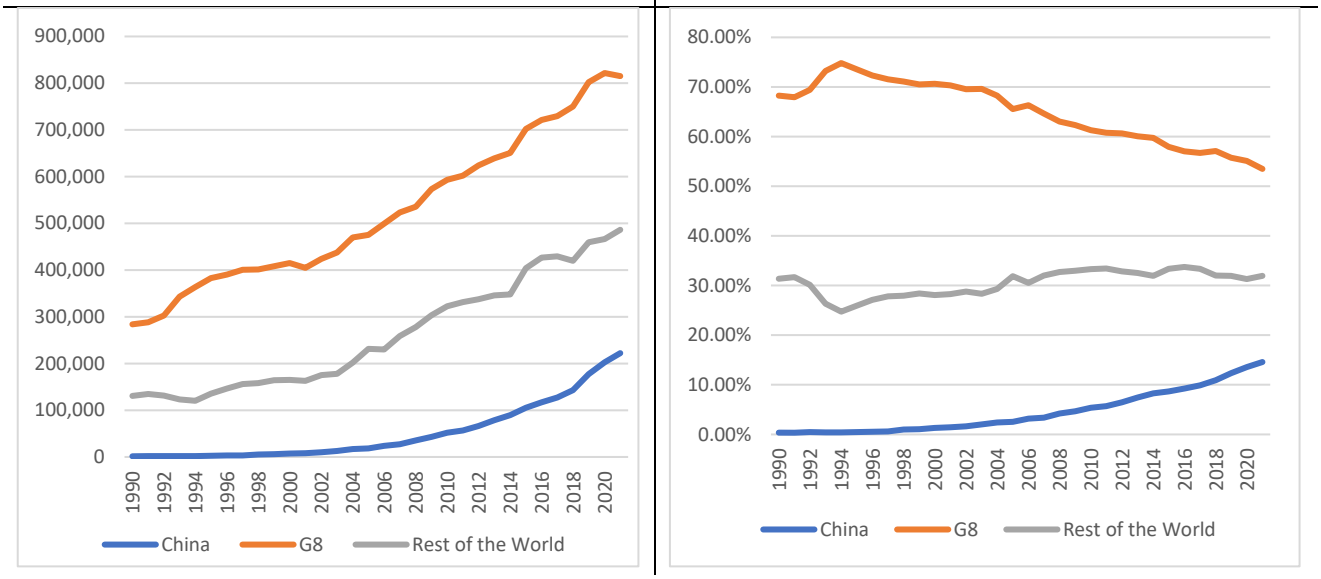
Within research publications, a particularly relevant role is played by health sciences. After 1990, these subjects stably represent about 40% of the total[3]. If we look both at the absolute number and at the relative weight of this field on world publications, the trends do not seem to be different from those observed for publications in general: we still observe an increase in the publications of Chinese researchers since 2000s, with a larger speed than other areas of the world (figure 2a), which is

[3] Source: authors' elaborations on WoS.

reflected in what seems to be a substitution between Chinese publications and the G8 (mainly U.S.) ones (figure 2b).

Fig. 2 – Publications in health-related sectors

a) In absolute values | *b) As % of total countries' publications*

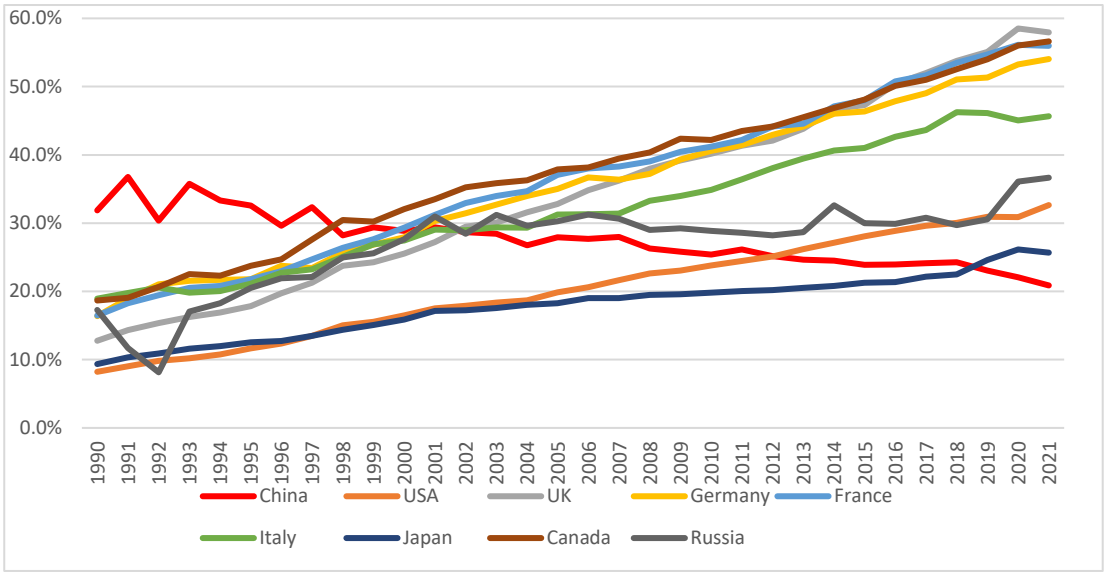


Source: authors' elaborations on WoS data.

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

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

Fig. 3 – Share of health-related publications in collaboration with other countries



Source: authors' elaborations on WoS data.

4.2. A focus on our database

The methodology described in section 3.1 has allowed to identify different groups of publications for China and the U.S. (see Table 2).

Table 2 – Number of publications in each subset

	2018_TOP5	2021_TOP5		
		Tot	Of which TOP5_COV	Of which TOP5_NoCOV
China (total)	***6979***	***14593***	***2342***	***12171***
of which				
only Chinese affiliations	5,011 (71.80%)	10,999 (75.37%)	1,704 (72.76%)	9,215 (75.71%)
Internationally co-authored	1,968 (28.20%)	3,594 (24.63%)	638 (27.24%)	2,956 (24.29%)
U.S. (total)	***30992***	***43308***	***6781***	***36527***
of which				
only U.S. affiliations	23,358 (75.37%)	31,515 (72.77%)	5,041 (74.34%)	26,474 (72.48%)
Internationally co-authored	7,634 (24.63%)	11,793 (27.23%)	1,740 (25.66%)	10,053 (27.52%)

Source: authors' elaborations on WoS data.

A first glance to the different sub-sets of data highlights the prevalence of national publications, both for China and for the U.S. Despite an evident difference in terms of size, in both countries in more than 70% of cases all the authors of the considered publications have a national affiliation. A difference that seems to emerge between China and the U.S. is a slightly higher tendency of the former towards international co-authorships when dealing with COVID-19 (27.24% against 25.66%).

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

154 against 185 for the U.S.). However, the shrinking for China is more accentuated, amounting to a decrease of 29% against 17% for the U.S..

Table 3 – Number of countries participating in COVID-19 and Non-COVID-19 networks within 2021_TOP5 networks

	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 on WoS data

At the *single publication* level (table 4), COVID publications seem to involve, instead, on average, a slightly larger number of countries. This might suggest that the COVID network revolves around a lower number of countries, but with more structured relations across a larger number of partners per publication. For China this is more evident given that, compared to pre-COVID collaborations, the publications in the top 5 sectors under scrutiny are, on average, participated by a lower number of countries.

Table 4 – Average number of authors and countries for international co-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 on WoS data

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

4.3. Social network analysis

Having seen this first average results, it seems useful to further deepen the analysis of the COVID and non-COVID networks, by performing a social network analysis (SNA), which might provide further information about the differences or analogies between the different subgroups[4].

Table 4 and 5 show the main results of the SNA for the various subsamples.

Table 4 – 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

[4] The analysis is performed being aware of the well-known difficulties in statistical testing applied 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.

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 on WoS data.

Table 5 – 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 on WoS data.

China's networks generally have a smaller number of nodes and edges compared to the U.S., confirming the presence of a smaller and less interconnected publication landscape. Despite a growth in the number of nodes for the US and a substantially stable number of nodes in China, in the TOP5 sectors both countries show a decrease in the number of edges from 2018 to 2021. This indicates a tendency towards 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 nets have relatively lower densities than 2018 ones, 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 in ego-centered networks assume the same interpretation than density (Perry et al., 2018).

Few more information about the shape of the networks can be retrieved from the comparison 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. In this metric, the 2021 U.S. network shows a slightly higher degree of centralization compared to the 2021 China network. This suggests that a smaller subset of nodes in the U.S. network have a higher number of connections compared to China. Strength centralization add to this information the weight of the connections: in our framework, it measures the extent to which the total amount 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 co-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 centralization, areas of research with a lower number of publications will have less likelihood to have higher strength centralization. We take into account this aspect by dividing the strength measure by the total number of publications in the network.

Delving into our main object of study, the possible impact of COVID-19 on the transnational publication networks, the following elements emerge. The COVID network in both countries has fewer nodes and edges compared to their respective overall 2021 Top5 networks, confirming the descriptive evidence that COVID-19 research publications involve a more limited number of countries for both China and the U.S.. Further, the density/reciprocity in these networks is lower than the overall 2021 networks and the 2021 NON-COVID 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 network is relatively high, but its value in both China and the U.S. is notably lower than in the other networks. Given that transitivity is a vital measure of local clustering pattern, this lower value indicates that COVID-19 research publications are characterized by less clustered collaborations compared to the general research landscape. The COVID networks show instead the highest values for degree centralization, indicating that few nodes catalyze a higher proportions of connections, acting as co-leaders with China/the U.S.. This is confirmed by the degree and the strength centralization, once considering the structurally lower number of publications focused on COVID-19 with respect to the other samples. In fact, they both show higher numbers with respect to all 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-type network - with China/ the U.S. and 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 on a multi-lateral and balanced way.

In conclusion, this social network analysis highlights the differences between publication networks centered on China and the US., as well as the impact of COVID-19 research on these networks. The COVID networks show distinct characteristics in terms of size, connectivity, and centralization. They appear, both in the case of China and of the U.S., to be more exclusive, as well as less centralized in terms of connection strengths, and still exhibit clustering patterns. These findings could be partially a consequence of a time issue: research about COVID-19 had to be performed rapidly during 2021 in order to offer solutions to the pandemics in the shortest time possible. This meant that few existing research networks, compared to similar area of research, could have been structured or re-oriented towards COVID. At the same time, COVID-19 networks seem nonetheless 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 co-publications is made with the U.S. as a major partner (see also Table 10). In particular, for what concerns COVID-19 related publications, China shares with the U.S. 299 out of 638 publications in its TOP5 sectors, corresponding to 46.87% of the total. When looking at the peculiar results obtained in the social network analysis for COVID publications, therefore, one could suspect that, rather than indicating a specificity of COVID-19 research as such,

they are more driven by the role played by the U.S. in this area of research. To exclude this, we have repeated the social network analysis excluding all the publications that the two country shares in their respective TOP5 sectors. Results are presented in table 6 and 7 and are consistent with the main ones.

Table 6 – Social network analysis statistics – China excluding co-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

Table 7 – Social network analysis statistics – the U.S. excluding co-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

Finally, we analyze how the assortativity metrics further characterize the networks under consideration (Table 8). First, in line with the evidence found in general for egocentric networks (Gupta et al., 2015), we find a strong tendency toward a disassortative nature, i.e., the tendency to collaborate with non-similar partners in terms of connections, which is also driven by the structural properties of this specific class of networks. Nevertheless, when disaggregating the 2021 net between COVID and non-COVID publications for China, we find a smaller tendency to disassortativity in the COVID-19 network (corresponding to a coefficient with a smaller absolute value). For the U.S., the case is reversed, as non-COVID network appears to be even assortative, and are coupled with a very disassortative COVID network.

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

Table 8 – 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 on WoS data.

Table 9 – Assortativity statistics – excluding reciprocal co-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 on WoS data.

4.4. A taxonomy of the collaborative behaviors

Once depicted the framework related to the shape and density of the overall networks, it might be worth investigating more about the behavior of the single partner countries involved in research in the selected sectors with China and the U.S.. The specific questions we would like to answer to are the following: what is the behavior of the partner countries of China and the U.S. in the 2021_TOP5 networks? Are they more focused on COVID-19 related research or not? Are they joining those networks mainly to enter COVID-19 research?

A first note to be made with regards to this is in relation to the TOP10 country partners in the selected sectors. For what concerns China (Table 10), the U.S. is the first partner in all the groups and sub-groups under consideration. Between 2018 and 2021 in TOP5 sectors, however, the U.S. have seemed to lose a bit of their centrality, when compared to the second partner (Australia in 2018 and England in 2021). This is even more accentuated in the COVID-19 subset, when the first-to-second partner ratio is 2:1. In comparison, no similar trend seems to emerge for the U.S. (Table 11), when the distance between England as the first partner and China as the second seems unchanged across all the groups.

Table 10 – Top 10 country partners for 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 on WoS data.

Table 11 – Top 10 country partners for 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 on WoS data.

In order to further deepen the possible effect of COVID-related research on the networks, a first evidence about the dynamic of research groups can be found in Table 12, 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 they started in 2021 ("Joiners") and (c) they were collaborating with China/the U.S. in 2018 and continue to do so (others). Although the total number of countries co-publishing with China does not change substantially (152 in 2018 vs 150 in 2021), we observe a relatively large turnover, with 20 leavers and 18 joiners. Conversely, the U.S. have substantially increased their partners, from 177 to 188. China's leavers as well as joiners, however, are weak countries in terms of number of publications: against a total average of 23.9 publications per country in 2018 and of 45.12 publications in 2021, these two groups 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 a higher volatility, in particular with respect to relations that might appear as more peripheral (i.e. smaller in numbers). This seems to point to a difficulty of the Chinese research system so far to act as a stable catalyser in this research field, in particular for marginal collaborators.

Table 12 – 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 on WoS data.

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

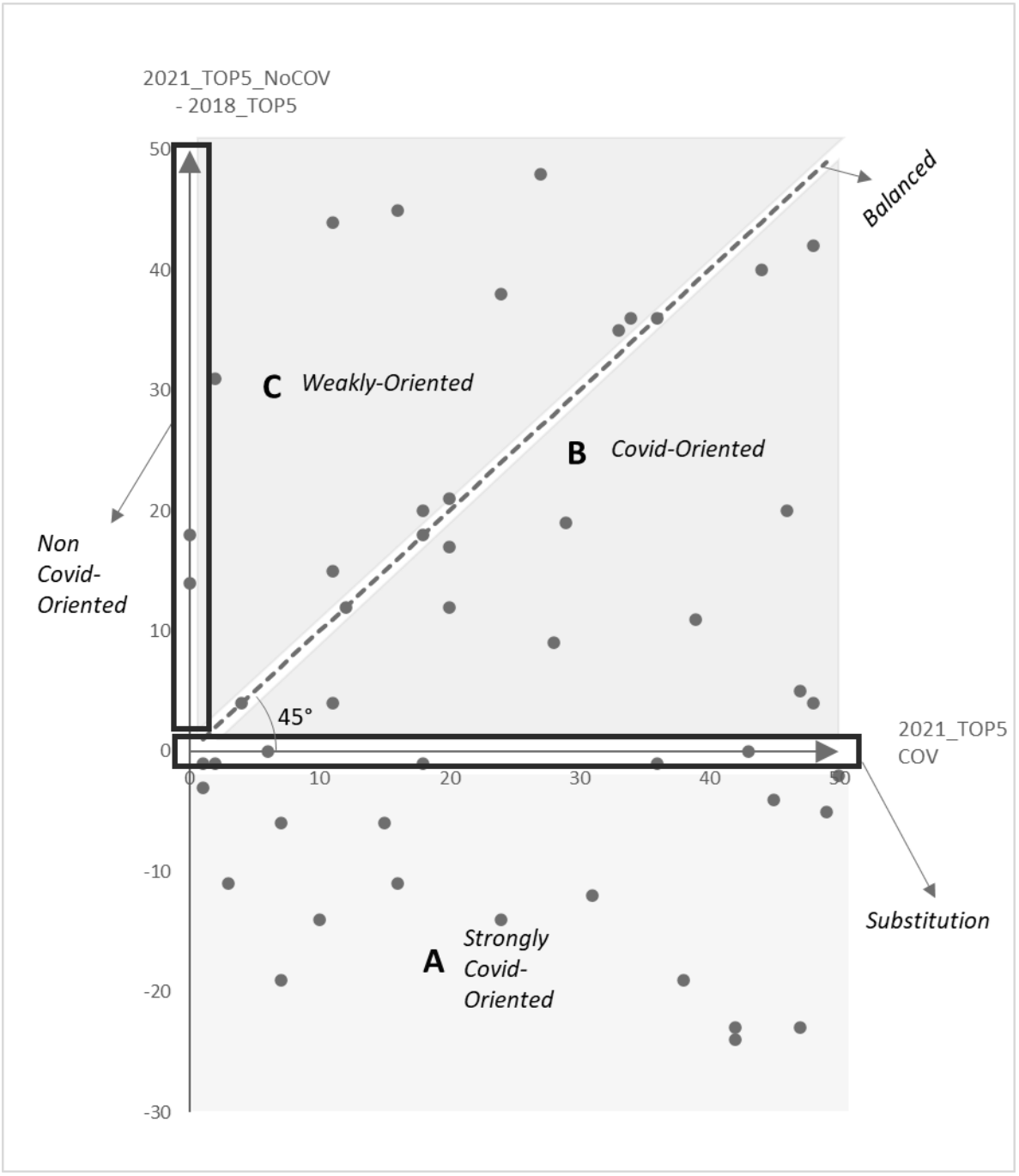
1. The number of 2018 co-publications with China/the U.S. in TOP5 sectors;
2. The number of 2021 co-publications with China/the U.S. in TOP5 sectors related to COVID-19;
3. The number of 2021 co-publications with China/the U.S. in TOP5 sectors unrelated to COVID-19.

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

We can read the taxonomy through the theoretical graphical representation presented in Figure 4, in which the x axis represents the amount of 2021 COVID publications, and the y axis is the difference between 2021 non-COVID publications and 2018 publications in the TOP 5 sectors. Starting from the lower quadrant of the graph, we find:

a) STRONGLY COVID-ORIENTED countries (A area): Countries that co-publish mainly in COVID-19 related research, and that decreased the amount of non-COVID research compared to 2018. Mathematically, these are countries for which the difference between 2021 non-COVID and 2018 is negative, while they have COVID co-publications.
b) SUBSTITUTING countries (x axes): In these countries the number of non-COVID 2021 publications is the same as 2018 top 5 publications and they also have a positive amount of COVID related publications. We define these as SUBSTITUTING in that any additional publication made by these partners compared to 2018 is focused on COVID research.

Figure 4 – A taxonomy of the countries according to their collaborative behavior in COVID vs Non-COVID related publications (dots are hypothetically placed)



Source: authors' elaboration on WoS data

a) COVID-ORIENTED countries (B area): This group exhibits a positive difference between the 2021 non-COVID publications and the 2018 ones. However, this positive difference is lower than the number of COVID-19 related publications.
b) BALANCED countries (bisector): These countries have seen a growth in the number of Non COVID-related publications compared to the total in 2018 in top 5 sectors, and this growth is numerically equivalent to COVID-19 publications. The growth of the intensity of the relation between these countries and China/the U.S. has been equally distributed between COVID-19 and non-COVID-19 research.
c) WEAKLY COVID ORIENTED countries (C area): These countries have a more limited interest in publishing in COVID related area: while they still publish articles related to

COVID, their number is lower than the difference between 2021 non-COVID and 2018 publications.

d) Non-COVID ORIENTED (y axis): The research groups of these countries, while still increasing the collaboration with China/the U.S. in the TOP5 sectors in 2021 compared to 2018, chose to do so only on non-COVID topics; in other words, the COVID related publications are null, while the 2021-2018 difference is positive.

We report the results of this taxonomy in Table 8.

Table 8 – 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 on WoS data.

It is interesting to note that 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 other figures seem to indicate that, compared to the U.S., the Chinese network has been less able to attract countries into COVID-19 related research compared to other topics of the same area.

The most relevant figure is the one related to the COVID-ORIENTED group of countries: it represents almost 24% of total partners for the U.S., while only 8% for the Chinese network. Even if the number of the strongly COVID-oriented partners is higher for China, if we also include the COVID-oriented category, the Chinese network shows to be less attractive than the U.S. one (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 13).

Table 13 – 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 on WoS data.

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

To reply to this point, we built up a pseudo-transition table representing the extent to which countries not or weakly oriented towards COVID-19 research with China are instead strongly engaged in COVID-19 research with the U.S.. The results, presented in Table 14 for the whole samples and in Table 15 when excluding publications involving China-U.S. relations, give a quite clear picture on this point.

Table 14 - Pseudo-transition tables: from Non- and/or Weakly-COVID oriented with China/the U.S. to Strongly COVID-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 on WoS data.

Table 15 - Pseudo-transition 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 on WoS data.

The answer seems to show that there is not a scarce propensity or possibility in collaborating on COVID-19 in general, but rather to collaborate on the topic *with China*: 18% of the countries that do not have any COVID-19 shared 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 having a weak orientation to COVID-19 co-publication with China. The result is even stronger when we exclude from the analysis the publications where China and the U.S. are together: the figures raise in fact to 26% in the first case and to 37% in the second. This might indicate that in the co-publications where the two countries are present, other actors join more because of the presence in the network of the U.S, rather than of China.

Finally, it has to be highlighted that this trend is not a bilateral one: when we look at the countries not oriented to collaborate on COVID-19 with the U.S., we find that none of them has a strong COVID-

related collaboration with China, and the transition remains very limited also including the countries that are weakly COVID-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 has declared the intention to transform the country in a world leader in science and technology by 2050 (Cao et al., 2006; Cao et al., 2020). In line with this aim, in the last few decades China has been massively investing in order to overcome the U.S. in the role of technological leader worldwide (Sharif, 2015). This is done not only counting on the wide national market, but also assuming a leadership position in the international research scenario and steadily increasing the R&D expenditure, which is already higher than Japan and Germany in terms of contribution to the global funding, reaching the EU and rapidly closing the gap with the U.S. (Crane, 2023; Veugelers, 2017). The country is reported to currently be the leader in several key technologies, such as advanced explosive, nano-materials or drone technology, and can produce research that has a much higher impact than the U.S. competitor (Knott, 2023; Hurst, 2023).

The analysis carried out in this paper has aimed at identifying possible peculiarities in the COVID-19 research networks. Confronting the characteristics of China and of the U.S. has emphasized the presence of national specificities, while the comparison with non-COVID-19 research in the same fields has allowed to identify some peculiar traits of this net. As it is reasonable to expect, all the Chinese networks and subnets are smaller than the U.S.' ones, both in terms of edges and of nodes. Despite the increasing presence of China in the international research scenario, and the overtaking of the U.S. in terms of relative weight in transnational publications, in the sectors under scrutiny its international system still appears to be smaller in size and less interconnected.

The COVID-19 net is, in both countries, more fragmented and less connected, involving a lower number of countries in comparison to non-COVID research net. At the same time, this network sees the presence of some nodes catalyzing a relatively higher number of relations. This is a somewhat unexpected result, given that the world-wide impact of the pandemic might have induced a higher degree of collaboration among different countries (Jit et al., 2021), and the willingness to put up a united front to find a solution to such a heavy, common problem. Even if, as already mentioned, some studies have found an initially increased propensity towards international collaboration on COVID-19 research, the relative fragility of COVID-19 nets identified by our research shows that in the long run, different forces might be in place, discouraging the increase in TRNs. For example, 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), the need to keep the secrecy on strategic findings, political tensions between states reducing the levels of trust, specific policy attitudes towards self-sufficiency/cooperation in emergencies.

Specifically on the role played by China in the COVID-related research network, our results seem to point neatly towards a lower capacity of the Chinese research system to catalyze scientists from other

countries to study COVID-related issues in comparison to the U.S. Despite being the country where the pandemic originated, China has been less engaged in international researches dealing with COVID-19 than in other explorations in the same scientific sectors but on different specific topics. This cannot be said for the U.S. research system, which has proved to be able to act as a more stable and stronger attractor (and coordinator) of international scholars eager to engage in COVID-related research. This shows that there is not a scarce interest towards COVID-19-related co-publications in general, but rather a relatively lower propensity or possibility to collaborate on the topic *with China*.

With the currently available data is not possible to understand if this is due to a lower 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, in order to relate this result with relevant aspects such as specific policy measures, degree of stability of the existing relations and role played by trust, weight of national intervention on the choices of individual researchers, and so on.

What seems already to be clear is that China is proposing itself as a global player not only in the science and technology field in general, but also in the more specific health-related sector. This is proved by the increasing importance that the Health Silk Road has 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 BRI to "an emerging diplomatic initiative for promoting health cooperation in a world increasingly threatened by proliferating public health emergencies" (Cao, 2020, p. 19), and it is seen as particularly important especially 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, it is very relevant to continue underlining the importance of policies aimed at favoring international collaborative behaviors able to facilitate joint efforts to face globally relevant issues.

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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 SNA

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

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

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

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

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

Where k_{max} is the maximum degree in the network, while 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, while S_i is the node-level strength.

Finally, we also exploit the potential of the indexes developed by Fagiolo, Reyes and Schiavo (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 use it focusing on the patterns of connections (edges) in the network. By measuring it, 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 neighbours, with the average number of connections of the neighbours; the strength assortativity coefficient, which measures the correlation between the number of publications in which each node participates (the nodes' strength) and the average number of publications in which its neighbor participate; and the weighted assortativity, i.e. the assortativity weighted for the strength.

A very final note is due to inform the reader that all employed metrics range from 0 to 1, with the exception of the assortativity ones, which being correlations range from -1 to 1, and of the strength centralization which depends on the distribution of the weights.