Journal of Economics Library
www.kspjournals.org
Volume 8 September 2021 Issue 3

Dynamics of science under period of crisis and environmental threat

By Mario COCCIA [†]

Abstract. The purpose of this study here is to explain the dynamics and characteristics of research fields in the presence of crisis. This paper focuses on effects of global pandemic crisis of COVID-19 (Coronavirus Disease 2019) in science dynamics. Results suggest that crisis-driven research field is characterized by an unparalleled velocity of scientific production that supports scientific and technological advances, open access and document type with short notes and papers. Understanding the dynamics of science and its consequences during the crisis is of critical importance for planning and allocating resources toward positive societal impact.
Keywords. Dynamics of science, Research field, COVID-19, Pandemic crisis, Environmental threats, Crisis management, Scientific advances, Technological change.
JEL. F21, F68, O53, K23.

1. Introduction

The explanation of dynamics of a research fields driven by crisis is critical to science and society for allocating resources and planning toward positive societal impact (Coccia, 2020; Coccia & Bellitto, 2018; Sun *et al.*, 2013). In this context, the evolution of studies concerning the novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) that caused the Coronavirus Disease 2019 (COVID-19) can clarify characteristics of research fields and research behavior in conditions of crisis directed to solve the problem of global pandemic (Coccia, 2021; 2020a, 2018; Dos Santos, 2020; Fanelli & Glänzel, 2013; Fortunato *et al.*, 2018; Sun *et al.*, 2013).
The research questions of this study are:

- How does a new scientific field driven by crisis evolve compared to established research fields?
- What are the characteristics of research fields and research behavior under conditions of crises and environmental threats?

This paper confronts these questions here by developing an inductive study focused on scientific documents in COVID-19 to analyze and explain different characteristics of the dynamics of science in period of crisis are critical to science and human society. This study is part of a large body of research that endeavors to explain how scientific fields and new technology emerge and evolve in a period of crisis to clarify general characteristics for designing research policies directed to progress of science in society (Ardito

[†] CNR, National research Council of Italy & Yale University School of Medicine, 310 Cedar Street, Lauder Hall, Suite 118, New Haven, CT 06520, USA.
☎. + 85287-4804 ✉. mario.coccia@cnr.it

et al., 2020; Coccia 2018, 2020; Coccia & Bozeman 2016; Coccia & Wang, 2016; Gibbons *et al.*, 1994).

2. Theoretical framework

The investigation of the research field of COVID-19, driven by a global crisis, is critical to science and society to explain how dynamics of science achieves and sustains new knowledge, and innovative drugs to solve this health and social issue that threats nations and global economy (Guerrieri *et al.*, 2020; Di Girolamo & Meursinge-Reynders, 2020; del Rio-Chanona *et al.*, 2020; Ebadi *et al.*, 2020). Current literature is investigating different aspects of COVID-19, such as Haghani & Bliemer (2020) that perform a comparative analysis across different epidemics (e.g., SARS, MERS and 2019-nCoV literature) showing that studies about epidemics are linked to epidemic control, chemical constitution of the virus, innovative treatments, vaccines and clinical care. Zhang *et al.* (2020) also investigate different infectious diseases and show that scholars always responded quickly to public health emergencies with an accelerated increase in the production of publications driven by disciplines of virology and immunology. Ebadi *et al.* (2020) analyze temporal evolution of COVID-19 research through machine learning and show that research communities focus their studies on high-risk groups and people with comorbidities. Di Girolamo & Meursinge Reynders (2020) investigate characteristics of scientific articles during the initial phase of COVID-19 pandemic crisis and suggest that the majority of early publications on COVID-19 are explorative studies with tentative results. In this research field, Belli *et al.* (2020) show that international collaboration is growing in all countries to support science advances to cope with COVID-19 pandemic crisis. Atlasi *et al.* (2020) argue that the literature on COVID-19 is increasing with a high and fast growth. New results can be used for an effective management of research and allocation of budgets to novel studies in order to avoid duplication of information. This strategy can be appropriate for prevention, control, and treatment of COVID-19 and new mutations of the novel coronavirus. Pal (2021) demonstrates that the rate of publication growth (1600%) reveals a synergic response of researchers to combat pandemic threat of COVID-19 and its variants. Moreover, many scholarly publishers have disclosed their preprint servers to make the publications available immediately in Open Access to accelerate solutions for COVID-19. In this field of research, publishers occupied almost 70% of articles, and about 25% of new studies were sponsored by 300 funding agencies. Findings also reveal that the majority of contributions has occurred in medical science, focusing on virology, immunology, epidemiology, pharmacology, nursing, etc. The most active academic hubs for scientific production concerning COVID-19 are located in the USA, China, Italy, and the UK. The advanced countries produced more than 50% of the global research output about COVID-19 with an intensive collaborative research across manifold countries and disciplines. Sachini *et al.* (2021) investigate the evolution of publications in all COVID-19-related peer reviewed papers that

have been (co)-authored by researchers that are affiliated with Greek institutions. Findings indicate that there is a steady increase in the number of publications and number of scientific collaborations over time. In addition, at a cross-country level, results suggest that higher education and government sectors contribute the most in terms of scientific outputs. On an international scale, a significant amount of publications (roughly 20%) is due to countries having "traditionally" major scientific impact in the field of medicine.

This study here develops, in this new research stream, an inductive analysis, which explains as far as possible dynamics of science and underlying relationships driven by crises, such as studies about COVID-19, to understand characteristics of the research behavior in the presence of crises and environmental (Guerrieri *et al.*, 2020; Di Girolamo & Meursinge Reynders, 2020; del Rio-Chanona *et al.*, 2020; Ebadi *et al.*, 2020; Xu *et al.*, 2021). In this context, the study shows a preliminary comparison of the growth of different pandemics in the initial phase of diffusion to assess the evolutionary paths of COVID-19. In particular, the study considers the initial growth of COVID-19 in comparison with:

- Middle East respiratory syndrome (MERS) that is a viral respiratory disease caused by a novel coronavirus (Middle East respiratory syndrome coronavirus, or MERS-CoV) that was first identified in Saudi Arabia in 2012 (WHO, 2021)
- Human immunodeficiency virus infection and acquired immunodeficiency syndrome (HIV/AIDS) that is a spectrum of conditions caused by infection with the human immunodeficiency virus HIV), a retrovirus. The first news story on the disease appeared May, 1981 (Sepkowitz, 2001).
- Zika virus disease that is caused by a virus transmitted primarily by Aedes mosquitoes, which bite during the day (WHO, 2021a).
- H1N1 (H1N1pdm09) virus that was detected in the United States in 2009 and spread quickly across the United States and the world. This new H1N1 virus contained a unique combination of influenza genes not previously identified in animals or people. This virus was designated as influenza A (H1N1)pdm09 virus. (CDC, 2021)

In addition, the paper makes a comparative analysis between the evolution of studies concerning the COVID-19 driven by crisis of global pandemic and research fields associated with serious respiratory disorders, such as Chronic Obstructive Pulmonary Disease (COPD) and lung cancer that are not driven by exogenous shocks. COPD is defined as a disease state characterized by the presence of airflow obstruction due to chronic bronchitis and emphysema. COPD is a highly prevalent disease affecting >10% of the population worldwide. The first manifestations occur at the cellular level with biochemical processes that lead to inflammation. Typically, the disease presents in the fourth or fifth decade with subtle symptoms, such as morning cough productive of mucoid sputum or simply an insidious progression of exertional dyspnea (Decramer & Cooper, 2010). COPD is thought to result

from an accelerated decline in forced expiratory volume in 1 second (FEV1) over time (Lange *et al.*, 2015). Moreover, it is well known that COPD is a very common disease with great morbidity and mortality (Halbert *et al.*, 2006; Siafakas *et al.*, 2018). The other research field compared is lung cancer: "that forms in tissues of the lung, usually in the cells lining air passages" [as defined by the National Cancer Institute (2021)]. Lung cancer is one of the main diseases in several developed countries and a leading cause of cancer death worldwide.

The comparative analysis of the evolution of crisis-driven research fields, such as COVID-19, to other research fields that are not driven by crises and environmental threats (e.g., COPD and Lung Cancer) can reveal main differences to clarify characteristics and properties of the dynamics of science under conditions of crises to design research policy for efficient allocation of resources directed to a positive impact in science advances and society (Figure 1).

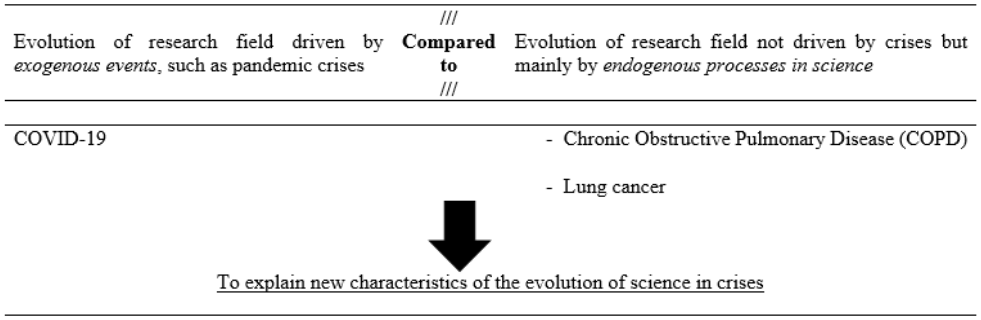

Figure 1. *Investigation of research fields and research behavior in a period of crises.*

2. Methods and materyals

2.1. Source and research setting

The study uses data of Scopus (2020) to detect scientific documents having in title, abstract or keyword the terms connected with respiratory diseases, such as: "COVID", "COPD", and "LUNG CANCER". Scientific products are appropriate units of analysis that can explain the structure and evolution of science.

Period under study: From 1st April to 31 December 2020, using daily data of document results from Scopus (2021). The year 2021 is not considered because the scientific production is on-going. Moreover, trends of research fields under study consider the first published documents and different periods:

- 1929-2020 for lung cancer
- 1969-2020 for COPD
- and finally, 2019-2020 for COVID-19

2.2. Measures

– Accumulation and development of knowledge in research fields under study here (COVID-19, COPD and Lung Cancer) are measured with

total document results given by: article, letter, review, note, editorial, conference paper, short survey, book chapter and conference review. In particular, data are gathered from Scopus (2021) daily from April 2020 onwards for 420 days.

- Documents of research fields under study per subject areas (e.g., medicine, biochemistry, genetics and molecular biology, etc.)
- Document type of research fields under study (i.e., article, letter, conference paper, book chapter, etc.)
- Documents of research fields under study per source title, such as journals.
- Documents of research fields under study per affiliation, such as universities, public and private research labs, hospitals, etc.
- Documents of research fields under study per funding sponsor, such as National Science Foundation, National Institutes, etc.
- Documents of research fields under study per countries.

3.3. Data analysis and procedure

Question 1 (evolution of crisis-driven research field compared to other related fields)

In order to answer the first research question of how a scientific field evolves in a period of crisis compared to established research fields not crisis driven, the method of inquiry is as follows.

Methods to explain question 1

Data of documents (in short, Docs) per research fields i (i = COVID-19, COPD and Lung Cancer) are gathered daily from 1st April 2020 to 6th June 2021.

It is calculated the daily growth (%) of documents (Docs) per research field (i) given by:

$$\Delta Docs\ (\%)\ of\ reserach\ field\ i\ (increment) = \left[\frac{(Docs_{day\ t} - Docs_{day\ t-1})}{Docs_{day\ t-1}}\right] \cdot 100 \quad (1)$$

The percent increment is calculated from April 2020 to June 2021 for all three research fields (COVID-19, COPD and Lung cancer); for COVID-19 the period is also divided from April to July 2020, from August to December 2020 and from January to June 2021 to better assess the different magnitude of the growth of this new research field over time. The data of documents and derived variables can be transformed in logarithmic scale to have a normal distribution for appropriate parametric analyses or to design graphs and trends with comparable values.

In addition, the study also compares the growth of different pandemics in the initial phase of diffusion to assess the evolutionary paths of COVID-19 from 2019 to 2021, compared to:

- MERS from t=2012 to t'=2015
- HIV from 1981 to 1984
- Zika virus disease (from 2010 to 2016)

– H1N1 (H1N1pdm09) virus (2009-2012).

The rate of growth is similar to equation [1] but it considers documents in the year t and initial year t' as indicated above.

Firstly, preliminary analyses of variables are descriptive statistics based on arithmetic mean, std. error of the mean, std. deviation, skewness and kurtosis to assess the normality of distributions and, if necessary, to fix distribution of variables with a *log*-transformation. Trends and bar graphs of research fields under study can show the type of development and annual increment in 2020 – 2021 in a context of comparative analysis.

Secondly, the study analyzes the evolution of documents as a function of time. The specification of relationship is based on a linear model that fits scatter data:

Linear model: $y_i = b_0 + (b_1\, t) + \varepsilon$ (2)

y= scientific documents in the research field i (i= COVID-19, COPD and Lung Cancer)

t = *time*= progressive series (N) indicating the time from 1 (1st day), 2 (2nd day), …, to 420 (420 day)

b_0= constant

b_1=coefficient of regression

ε= error term

Ordinary Least Squares (OLS) method is applied for estimating the unknown parameters of models [2] in regression analysis.

Thirdly, the study analyzes whether the difference of arithmetic mean of $\Delta Docs$ (%) [1] between research fields considered as independent groups (e.g., COVID-19=group 1 that is driven by crisis vs. COPD=group 2 not driven by crisis, etc.) is significant. In particular, the Independent Samples t-Test is applied to compare the means of two independent groups in order to determine whether there is statistical evidence that the associated population means are significantly different. The Independent Samples t-Test requires the assumption of homogeneity of variance -- i.e., both groups have the same variance and as a consequence Levene's Test is performed. After that, null hypothesis (H_0) and alternative hypothesis (H_1) of the Independent Samples t-Test are:

H_0: $\mu_1 = \mu_2$, the two population means are equal in groups

H_1: $\mu_1 \neq \mu_2$, the two population means are not equal in groups

The arithmetic mean of groups is compared considering pair of research fields under study as follows:

COVID-19 (group 1) – COPD (group 2),

COVID-19 (group 1) – Lung Cancer (group 3),

and COPD (group 2) – Lung Cancer (group 3).

Remark. Group 1 indicates a crisis-driven research field; Groups 2 and 3 are research fields not driven by crises but by endogenous factors to science dynamics.

This analysis is performed considering data from April to December 2020

for 260 days to assess the differences between means in the initial evolution of studies in COVID-19 and obtain stable results, since data of 2021 are ongoing.

Question 2 (characteristics of crisis-driven research fields and research behavior in a period of crises)

In order to clarify second question main drivers and additional characteristics of emerging research fields in crises to explain the dynamics of science, the method is as follows.

Methods to clarify question 2

Data analysis procedure here uses total number of documents published in the research field of COVID-19 from April to December 2020 and from January to June 2021 to assess variations of research behavior in crises considering:

- Main research areas supporting the evolution of the research field of COVID-19.
- Leading journals supporting the evolution of the research field of COVID-19.
- The most prolific institutions in the production of COVID-19
- The most important institutions that have funded studies in the research field of COVID-19 over time.
- Finally, a ranking of the most prolific countries in the research field of COVID-19 that have supported scientific and technological advances in this new research fields.

Statistical analyses are performed with the Statistics Software SPSS® version 26.

4. Results

- *Dynamics of research fields driven by crises compared to research fields (question 1)*

Pandemics is a very special condition in society and it is important to explain the behavior and characteristics in the research arena. First of all, the study also shows a comparison of the growth of different pandemics in the initial phase of diffusion to assess the evolutionary path of COVID-19. In particular, the study considers the initial growth of publications in COVID-19 compared to Middle East respiratory syndrome (MERS) from 2012 to 2015, HIV from 1981 to 1984, Zika virus disease (from 2010 to 2016) and H1N1 (H1N1pdm09) virus (2009-2012). Figure 2 suggests the unparalleled growth of publications in COVID-19 likely associated with the high number of deaths that has supported a lot of scientific research to solve this global socio-health issue (cf., Pal, 2021).

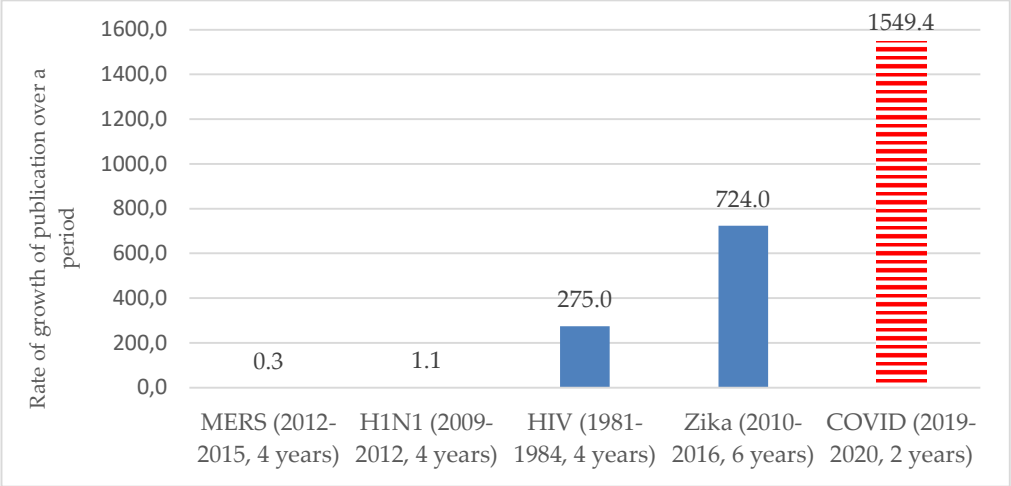

Figure 2. *Rate of growth of publications concerning some pandemics in the initial phase of diffusion.*

Figure 3 shows the evolution of research fields comparing COVID-19 having a crisis-driven origin in 2019 to lung cancer started in 1929 (though some occasional previous papers) and COPD originated in 1969 or thereabouts. Results suggest two different types of evolution of research fields:

- crisis-driven is associated with exogenous factors that generate shocks and environmental threats in socioeconomic systems and need to be solved in a short run.
- problem-driven is associated with a situation that causes difficulties in people and environment and needs to be solved in a medium run.

In this context, crisis-driven research field of COVID-19 has a sharply increase from 2019, whereas problem-driven research fields have a linear growth over time. In particular, the evolution of research fields of COPD and lung cancer, originated because of problems given by main diseases in society (problem-driven origin), suggests an linear equation of development of publications (y) given by $y(t)= \alpha+\beta t$ with an acceleration for lung cancer in 1975 (about 45 years after origin in 1929) and for COPD in 1995 (25 years after the origin), whereas the crisis-driven research field of COVID-19 originated with a pandemic and public health threat has an evolutionary paths associated with an exponential equation of development of publications: $y(t)= \alpha \cdot e^{\beta t}$ (cf. also figure 4).

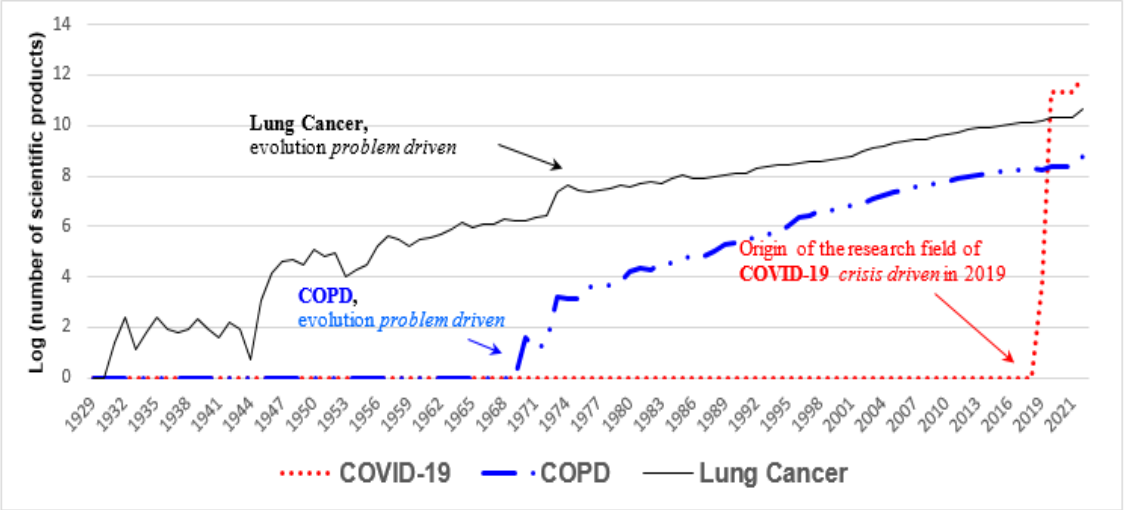

Figure 3. *Evolution of crisis- and problem- driven research field over time (last data included 6 June 2021). Note: Log scale is to have comparable trends.*

Figure 4 shows the initial evolution of the research field of COVID-19 with some chronological events given by the first cases in China in 2019, the alarming levels of spread and severity in Europe in March 2020 and the announcement of first vaccines in November 2020.

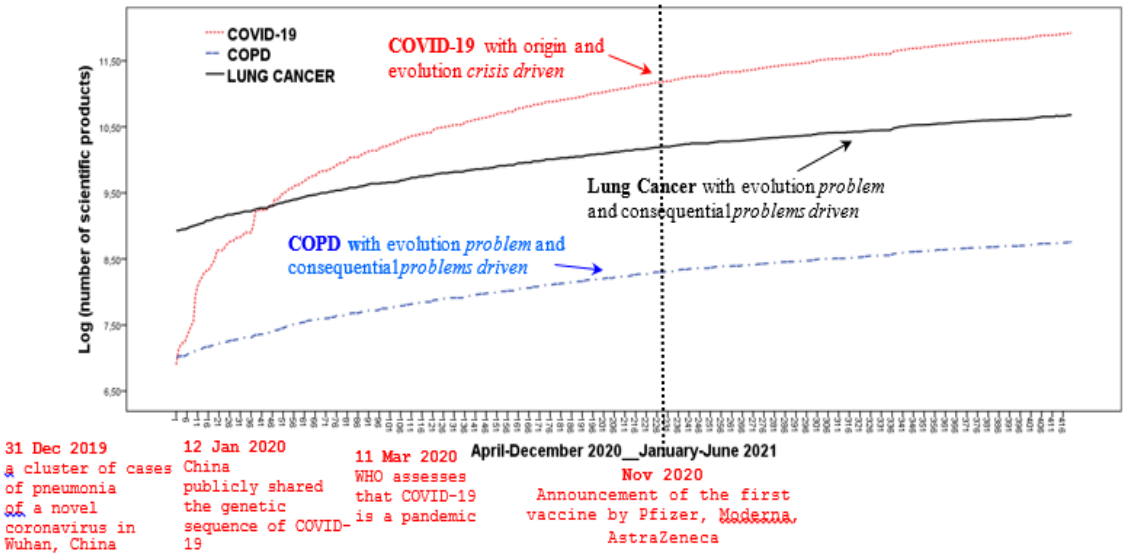

Figure 4. *Evolution of COVID-19 compared to COPD and Lung Cancer (t=420 days from April to December 2020 and January-June 6th, 2021). Note: COVID-19 = Coronavirus Disease 2019; COPD = Chronic Obstructive Pulmonary Disease; Log scale is to have comparable trends*

Table 1 considers the initial number of publications in COVID-19, COPD and lung cancer (first three years since origin). It is also important to observe that the annual scientific production of COVID-19 studies in December 2020 (i.e., 83,621 documents) has surpassed annual production of main research fields, such as COPD having 4,397 documents and in particular lung cancer having 29,362 documents in December 2020. Moreover, problem-driven

research fields have in the initial phase of origin an arithmetic growth of scientific products, whereas crisis-driven research fields, such as COVID-19, have and exponential growth because of overring problems and environmental threats in society that have to be solved rapidly.

Table 1. *Number of publications of research fields in first three years after origin*

year	COVID-19	year	COPD	year	Lung cancer
2019	57	1969	1	1929	1
2020	85,539	1970	5	1930	0
2021	on going	1971	3	1931	4
		2020	4,397	2020	29,362

Note: data of 9th June 2021 (Scopus, 2021)

Table 2 confirms the unparalleled evolution of the research field of COVID-19 compared to lung cancer and COPD. In particular, in April 2020 the research field of COVID-19 was at initial stage of evolution and had the lowest number of publications, whereas in June 2021 it has outclassed over other research fields (COPD and Lung Cancer) that have had a stable evolution over time. In fact, the average growth of the research field of COVID-19 is 1.2% daily from April 2020 to June2021, whereas other research fields have had a normal evolution with a steady growth equal to about 0.42% of daily publications (Figure 5). In addition, table 2 shows that the evolution of the research field of COVID-19 from April to July 2020 had an average growth accelerated of 3.16% daily, whereas from August to December 2020 has reduced the acceleration of scientific production, converging towards a steady average growth of about 0.65% daily, in the 2021 (January-June 2021) it is about 0.38%.

Table 2. *Descriptive statistics of scientific documents in the research fields of COVID-19, COPD and Lung Cancer based on 420 days from April 2020 to June 6th, 2021.*

Variables	Arithmetic Mean	Std. Error
COVID-19, documents (Docs)	68,067.61	2,135.79
COPD, documents	3,743.23	74.32
Lung Cancer, documents	25,119,04	504.17
$\Delta Docs$ (%) of COVID-19, daily increment	1.19	0.16
$\Delta Docs$ (%) of COPD, daily increment	0.417	0.024
$\Delta Docs$ (%) of Lung Cancer, daily increment	0.419	0.023
$\Delta Docs$ (%) of COVID-19, daily increment April-July 2020	3.16	0.56
$\Delta Docs$ (%) of COVID-19, daily increment August-December 2020	0.65	0.06
$\Delta Docs$ (%) of COVID-19, daily increment January-June 2021	0.38	0.04

Note: COVID-19= Coronavirus Disease 2019; COPD= Chronic Obstructive Pulmonary Disease

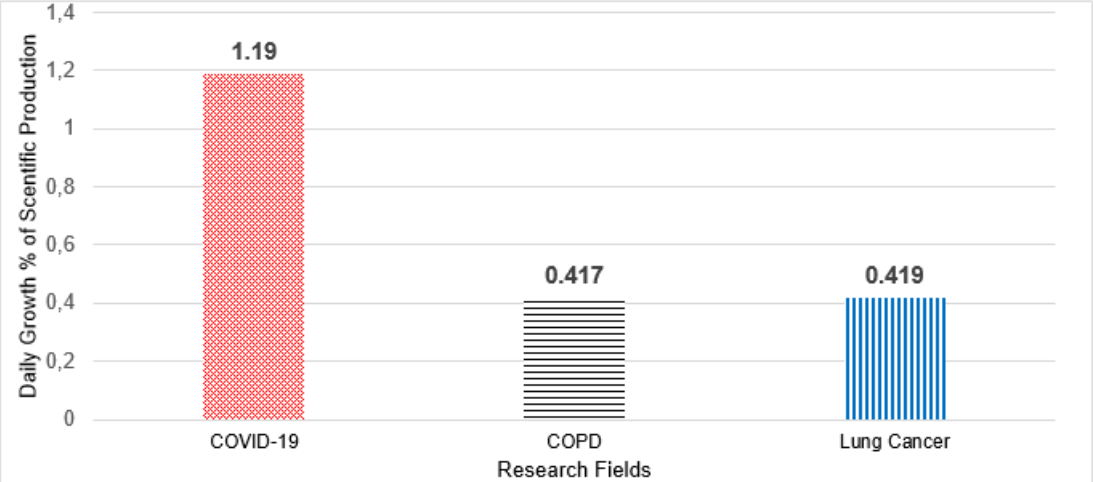

Figure 5. *Daily growth (%) of scientific production of research field based on 420 days from April 2020 to June 6th, 2021. Note: COVID-19= Coronavirus Disease 2019; COPD= Chronic Obstructive Pulmonary Disease*

Table 3 suggests that in the research field of COVID-19, an increase of 1 day, it increases the expected number of publications by about 360 units (*p*-value<.001), whereas in research field of COPD by about 13 units (*p*-value<.001), finally in research field of Lung Cancer, the expected number of publications increases by about 85 units (*p*-value<.001). This result confirms the unparalleled growth of scientific production in the research field of COVID-19.

Table 3.*Parametric estimates of the relationship of scientific production in research fields as function of time (T=420 days, from April 2020 to June 2021)*

	Model Linear COVID-19	Model Linear COPD	Model Linear Lung cancer
Constant α	–7619.01***	1102.74***	7209.64***
(St. Err.)	(323.46)	(3.78)	(30.34)
Coefficientβ *(time)*	359.56*** a	12.54*** a	85.08*** a
(St. Err.)	(1.33)	(.016)	(.13)
F	72915.44***	651540.61***	464061.02***
R^2	.994	0.99	.99

Note: *** *p*-value<0.001; a= predictor is a progressive series (N) indicating the time from 1 (1st day), 2 (2nd day) … to 420 (420th day) from April to December 2020 and January- 6th June 2021.

Finally, the Independent Samples t-Test compares the means of two independent groups in order to determine whether there is statistical evidence that the associated population means of ΔDocs are significantly different from April to December 2020 (2021 is excluded in this statistical analysis because it is ongoing). The *p*-value of Levene's test is significant, and we have to reject the null hypothesis of Levene's test and conclude that variances in groups under study are significantly different (i.e., Equal variances are not assumed), except mean $\Delta Docs$ (%) between COPD and LC that has *p*-value<.27 and as a consequence Equal variances are assumed (Table 4).

Table 4 shows main results about a statistically significant difference of arithmetic means of *ΔDocs* between groups. In particular, table 4 substantiates that:

- There was a significant difference in mean $\Delta Docs$ (%) between research fields of COVID-19 and COPD ($t_{264.809} = 4.69$, $p < .001$), suggesting a *different* evolution of these research fields
- There was a significant difference in mean $\Delta Docs$ (%) between research fields of COVID-19 and Lung cancer ($t_{263.118} = 4.727$ $p < .001$), suggesting a *different* evolution of these research fields
- Whereas, arithmetic mean of $\Delta Docs$ (%) between research fields of COPD and Lung cancer is not different but it is rather similar ($t_{505.496} = .161$ $p < .872$), suggesting a *similar* evolution of these research fields

Table 4. *Independent Samples Test*

		Levene's Test for equality of variances		*t*-test for equality of Means				
		F	Sig.	*t*	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference
$\Delta Docs$ (%), COVID-19/COPD	Equal variances assumed	35.53	0.001	4.690	510	0.001	1.186	.2528
	Equal variances not assumed			4.690	264.809	0.001	1.186	.2528
$\Delta Docs$ (%), COVID-19/LC	Equal variances assumed	37.28	0.001	4.727	510	0.001	1.194	.2524
	Equal variances not assumed			4.727	263.118	0.001	1.194	.2524
$\Delta Docs$ (%), COPD/LC	Equal variances assumed	1.204	0.273	.161	510	.872	.00758	.0470
	Equal variances not assumed			.161	505.496	.872	.00758	.0470

Note: N=256 days over April-December 2020 period. Δ=increment

The conclusion of these statistical analyses are that the rate of evolutionary growth of the research field of COVID-19 is statistically different from other normal research fields, such as COPD and Lung cancer. Hence, crisis-driven research field of COVID-19 has an accelerated and disproportionate growth compared to problem-driven research fields with the potential to lead to manifold scientific breakthroughs over time.

- *Results to explain the second research question on characteristics of research field and research behavior in the presence of turbulent crises*

The origin and accelerated growth of the crisis-driven research field of COVID-19 reveal some main characteristics to understand the dynamics of science in crisis. The most productive research areas in the research field of COVID-19 are mainly related to life science (Table 5). Of the top 10 research areas more than 53% of documents published on COVID-19 worldwide is in Medicine, Biochemistry, genetics and molecular biology has more than 8% and Immunology and microbiology has more than 5% (cf., Zhang *et al.*, 2020). In the top ten areas, there is also social sciences (more than 9%) and environmental science (about 3.5%) because manifold studies analyze

possible relations between air pollution and the spread of COVID-19 in society (Coccia, 2020a). The comparison of two periods in 2020 and 2021 shows the growth of computer science in 2021 and studies of psychology likely associated to side effects of containment policies of full lockdown (Coccia, 2021a). This research field of COVID-19 confirms the properties of science dynamics by Coccia (2018) that the emergence of a research field is in critical (parent) disciplines (e.g., medicine, biochemistry, genetics and molecular biology in the case study of COVID-19), and subsequently the evolution is driven mainly by few disciplines (3–5) that generate more than 80% of documents (*concentration of scientific production).*

Table 6 shows the top ten journals that have published more contributions on emerging research field of COVID-19. Five of the top ten journals are related to medicine (parent discipline; cf. Coccia, 2018). In the top ten, there are also journals related to environmental and sustainability science for investigating relationships between environmental pollution and the spread of COVID-19 (cf., also Zhang *et al.*, 2020). In the top ten, it is also important to note the presence of the journal "Medical Hypothesis" because in the initial phase of pandemic based on a novel coronavirus hardly known, a lot of scholars suggest multiple working hypotheses to explain likely determinants of transmission dynamics, consequences on health of people and effective treatments to reduce the negative impact of COVID-19 pandemic in society (cf. also, Haghani & Bliemer, 2020). In 2021 compared to 2020, the evolution of this research field is also driven by journals of psychology and interdisciplinary that enter in the top ten list having a higher number of contributions.

Table 5. *Top ten areas supporting the evolution of the research field of COVID-19*

Ranking	31 December 2020 Documents published, Disciplines	N.	%	6 June 2021 Documents published, Disciplines	N.	%
1	Medicine	57842	57.62	Medicine	97236	53.36
2	Social sciences	9377	9.34	Social sciences	19210	10.54
3	Biochemistry, Genetics and molecular biology	8560	8.53	Biochemistry, Genetics and molecular biology	15045	8.26
4	Immunology and Microbiology	5472	5.45	Immunology and Microbiology	9568	5.25
5	Nursing	3723	3.71	Computer science	8401	4.61
6	Pharmacology, Toxicology and Pharmaceutics	3554	3.54	Environmental sciences	7444	4.09
7	Environmental sciences	3502	3.49	Nursing	6936	3.81
8	computer science	3054	3.04	Engineering	6679	3.67
9	Engineering	2819	2.81	Pharmacology, Toxicology and Pharmaceutics	6058	3.32
10	Neuroscience	2480	2.47	Psychology	5646	3.10
	Total	100383	100.00		182223	100.00

Table 6. *Top ten journals leading the evolution of the research field of COVID-19*

Ranking	31 December 2020 Documents published in Journals	N.	%	6 June 2021 Documents published in Journals	N.	%
1	International Journal of environmental research and public health	737	14.87	International Journal of environmental research and public health	1702	18.43
2	Journal of medical virology	648	13.07	Plos ONE	1465	15.87
3	BMJ Clinical research from British Medical Association	615	12.41	Journal of medical virology	1025	11.10
4	BMJ from British Medical Association	576	11.62	BMJ	896	9.70
5	Plos ONE	562	11.34	BMJ Clinical research	875	9.48
6	Lancet	413	8.33	Sustainability (Switzerland)	719	7.79
7	International Journal of Infectious diseases	399	8.05	International Journal of Infectious diseases	670	7.26
8	Medical Hypotheses	354	7.14	Scientific Reports	658	7.13
9	Science of the total environment	327	6.60	Frontiers in Psychology	630	6.82
10	Sustainability	326	6.58	Lancet	594	6.43
	Total	4957	100.00		9234	100.00

The most prolific institutions in the research field of COVID-19 are Harvard Medical School and two Chinese organizations, Huazhong University of Science and Technology, and Tongji Medical College. The top 10 active institutions in COVID-19 studies are mainly academic institutions localized in specific advanced countries: 1 in the USA, 2 in China, 3 in England, 2 in Italy, 1 in France and 1 in Canada (Table 7).

Table 7. *The top ten prolific institutions in the production of COVID-19 studies*

Ranking	31 December 2020 Documents published, Research Institutions/Affiliations	N.	%	6 June 2021, Documents published Research Institutions/Affiliations	N.	%
1	Harvard Medical School, USA	1422	15.56	Harvard medical school	2325	15.76
2	Huazhong University of Science and Technology, China	1111	12.16	Huazhong University of Science and Technology	1591	10.78
3	Tongji Medical College, China	1056	11.56	University of Toronto	1579	10.70
4	The Institut national de la santé et de la recherche médicale, INSERM, the French National Institute of Health and Medical Research.	983	10.76	INSERM, France	1508	10.22
5	University of Toronto, Canada	908	9.94	Tongji Medical College	1477	10.01
6	Università degli Studi di Milano, Italy	776	8.49	University of Oxford	1395	9.45
7	University of Oxford, England	761	8.33	University College London	1289	8.74
8	Università di Roma la Sapienza, Italy	755	8.26	Imperial College London	1223	8.29
9	University College London, England	704	7.71	Università degli Studi di Milano	1209	8.19
10	Massachusetts General Hospital, USA	660	7.22	Università di Roma La Sapienza	1159	7.85
	Total	9136	100.00		14755	100.00

The top ten funding organizations that have supported the emerging research field of COVID-19 with the publication of documents are located in the USA, China, the UK, Europe (with European Commission) and Brazil. In particular, at December 2020, institutions in the USA have funded about 43% of published documents in top ten institutions, in China about 35%, in the UK roughly 12.5% of documents and finally in Brazil about 9%. In June 2021, funding role of US institutions is reinforced in the top ten with about 47%, China, UK and Brazil have a slightly. In 2021, a supranational institution given by European commission enters in the top ten of funding institutions with about 6%. Results show that the top funding institutions in scientific production of COVID-19 are public organizations, except Wellcome Trust that is a global charitable foundation, located in London (UK). In addition, Table 8 shows the driving role of public funding organizations in two large countries given by the USA and China that have funded more than 78% of documents on COVID studies among top ten institutions (cf., also *Zhang et al.*, 2020). De Roeck (2016) argues that scientific discovery is also due to main role of funding of governments and funding agencies.

Table 8. *Top ten institutions that have funded studies in the research field of COVID-19*

	31 December 2020			6 June 2021		
Ranking	Documents funded by	N	%	Documents funded by	N	%
1	National Natural Science Foundation of China	1901	30.84	National Institutes of Health, USA	3992	27.01
2	National Institutes of Health, USA	1641	26.62	National Natural Science Foundation of China	3689	24.96
3	National institute for health research, UK	422	6.85	U.S. Department of health and human services	1140	7.71
4	National Science Foundation, USA	411	6.67	National institute for health research, UK	1005	6.80
5	Wellcome Trust, UK	346	5.61	National Science Foundation, USA	963	6.52
6	National Institute of allergy and infectious disease, USA	344	5.58	National Key research and Devel program of China	912	6.17
7	Conselho nacional desenvolvimento Cient, Brazil	326	5.29	European Commission	881	5.96
8	Fundamental Research Funds for the Central Universities, China	277	4.49	National Institute of Allergy and infectious disease, USA	816	5.52
9	National heart, Lung and Blood institute, USA	256	4.15	Wellcome Trust, UK	709	4.80
10	Coordenecao de aperfeicoamento de pessoal de Nivel Superior, Brazil	240	3.89	Conselho nacional desenvolvimento Cient, Brazil	672	4.55
	Total	6164	100.00		14779	100.00

The evolution of research field of COVID-19 is driven mainly by scientific production in advanced and rich countries that have published about 78% of documents in the list of top ten countries that also includes China with about 13% and India with 8% (Table 9). This result further confirms the concentration of scientific production in specific geoeconomic contexts of

rich countries (Coccia, 2018). Coccia (2019) argues that nations produce science advances and new technology to endorse a socio economic power and leadership directed to take advantage of important opportunities or to cope with environmental threats in competitive settings. In general, underlying motivations of nations to produce science advances and new technology in society can be: endogenous power and leadership in international system, higher reputation in the international system with challenges to big science and path-breaking technology and economic growth and wellbeing of citizens.

Table 9. *Top ten countries with the highest number of documents produced in the research field of COVID- 19*

Ranking	31 December 2020 Countries of production	N	%	6 June 2021 Countries of production	N	%
1	United States	21285	30.37	United States	38155	31.06
2	China	9293	13.26	United Kingdom	15975	13.01
3	United Kingdom	9004	12.85	China	15092	12.29
4	Italy	7765	11.08	Italy	12664	10.31
5	India	5885	8.40	India	10654	8.67
6	Spain	3585	5.11	Spain	6505	5.30
7	Canada	3542	5.05	Canada	6357	5.18
8	Germany	3274	4.67	Germany	6227	5.07
9	France	3253	4.64	Australia	5718	4.65
10	Australia	3209	4.58	France	5489	4.47
	Total	70095	100.00		122836	100.00

Finally, a comparative analysis of crisis-driven research field and problem-driven research fields shows some main characteristics of the research behavior in crisis (Table 10).

Table 10. *Characteristics of publication in crisis-driven (COVID-19) and not crisis driven research fields (COPD and Lung Cancer), using data on 7th June 2021*

	COVID		COPD		Lung Cancer	
	Number	% of total	Number	% of total	Number	% of total
Total publication June 2021	152970		60798		449875	
Open access	116203	75.96	24616	40.49	162703	36.17
Type of documents						
Article	93563	61.16	44039	72.43	333986	74.24
Letter	18201	11.90	1281	2.11	13089	2.91
Review	16795	10.98	8645	14.22	55782	12.40
Note	8769	5.73	1227	2.02	8643	1.92
Conference	307	0.20	2256	3.71	13800	3.07

Results show that research behavior in crisis is mainly open access for a widespread diffusion of results for a higher social impact, in fact products in COVID-19 have about 76% of access, whereas in COPD is 40% and Lung cancer is 36%. In addition, scientific production has a higher publication density with short communication given by letters that in crisis-driven

research field of COVID-19 is about 12% (vs. 2-3% for COPD and Lung Cancer) and notes that have higher frequency of about 6% (vs. about 2% for COPD and Lung cancer).

5. Discussion

The inductive analysis here, based on case study of the research field of COVID-19, has theoretical implications to explain the dynamics of science and research behavior in periods of crises that generate scientific discoveries.

This study suggests that (Table 11):

- *Problem-driven* research fields are based on perception of the problem in nature and/or society (e.g., lung cancer, Alzheimer disease, environmental pollution, etc.) and the evolution is mainly due to endogenous processes in science that generate discoveries in the long run (Sun *et al.*, 2013).
- *Crisis-driven* research fields are due to a crisis, exogenous event, which generates environmental threats with elements of surprise in society having high priority goals of solution in a limited amount of time before can permanently damage socioeconomic and environmental systems (e.g., pandemic, war, etc.). The evolution of crisis-driven research fields has in the starting phase an exponential growth that fosters science advances and scientific discoveries in the short run.

In particular, some unique characteristics of the evolution of crisis-driven research fields and research behavior in crises that can be systematized with following empirical properties of the dynamics of science:

1. *Environmental threat.* Evolution of crisis-driven research field is due to a new and consequential environmental threats in human society, such as COVID-19 global pandemic crisis, supporting a high average rate of daily growth of scientific production (about 1.2% daily) that can generate scientific and technological breakthroughs in a *short run*.

Remark: Evolution of research field not crisis driven, called here problem driven, is based on average rate of daily growth of scientific production equal to about 0.4% that generates scientific breakthroughs in the *long run.*

2. *Concentration of scientific production.* Evolution of crisis-driven research fields field is pulled by few (parent) disciplines (3–5) that generate more than 80% of documents. In the case study of COVID-19 critical disciplines are given by medicine, biochemistry, genetics and molecular biology. This crisis-driven research field of COVID-19 confirms the property of science dynamics by Coccia (2018).

3. *Public research organizations of advanced nations.* The most active institutions in crisis-driven studies are mainly academic institutions localized in advanced countries.

4. *Public funding institutions of advanced nations.* Main funding institutions in scientific production of crisis-driven research fields are public organizations of rich nations and global charitable foundations.

Remark: Data show that in June 2020, in the initial phase of COVID-19 pandemic, premier biopharmaceutical companies (e.g., AstraZeneca, Merck, Novartis, Pfizer, Roche, etc.) funded scientific research in this global health

issue and some of them has generated scientific and technological breakthroughs given by new vaccines to treat this new infectious disease.

5. *Rich countries and global leadership*. Scientific production of crisis-driven research fields is due to specific geoeconomic contexts of rich countries that generate about 78% of documents. The most productive countries of crisis-driven research fields are nations direct to support their global leadership (cf., Coccia, 2015, 2017, 2017a).

Remark: This result is due to high levels of R&D investments in rich countries that support scientific and technological advances (Coccia, 2009, 2012, 2018a; Kealey, 1996; Price de Solla, 1986). These results can be due to critical socioeconomic factors of leading countries in supporting this crisis-driven research field in science and society as explained by Coccia (2019):

- Science advances and new technology are a source of socioeconomic power for countries to take advantage of important opportunities or to cope with consequential environmental threats in society.
- Science advances and new technology are drivers of economic and productivity growth for nations and of a higher wellbeing of citizens.
- Science advances and new technology increase reputation and recognition of nations worldwide to support an endogenous power in international system based on scientific and technological superiority that endorses their leadership and affects other geoeconomic regions to take advantage of commercial and political opportunities.

6. *Open source production*. Research behavior of crisis-driven research fields is mainly open access for a widespread diffusion of results for a higher social impact.

7. *Short communication*. Scientific production of crisis-driven research field has a higher publication density of short communication given by letters and notes to systematize quickly findings.

Table 11. *Evolution of research fields in science*

Origin		Problem driven	Crisis driven
–	Type of evolution	Linear in short and long run	Exponential in the short run, linear in the long run
–	Growth of scientific products in the initial phase of development	Arithmetic increment	Geometric/Exponential increment
–	Active institutions	Public research organizations and universities	Public research organizations and universities
–	Funding institutions	Public funding institutions	Public funding institutions and foundations
–	Prolific countries	Rich countries	Rich countries
–	Open Access	Low intensity	High intensity
–	Document type	Articles and conferences	Articles, letters and notes
–	Discoveries and paradigm shifts	Long-run	Short-run
–	Example	COPD, Lung Cancer	COVID-19

The main findings of this study suggest that in general research fields evolve with accumulation of "normal science" (e.g., COPD and lung cancer) that can have discontinuous transformations in the long run by new theoretical and empirical approaches that support the transition from an existing scientific paradigm to an emerging one (Kuhn, 1996). However,

what this study adds is that in the presence of consequential environmental threats for human society (such as COVID-19 global pandemic), crisis-driven evolution of research fields has accelerated rates of growth that generate discoveries and science advances in the short run to solve overriding problems and/or reduce the negative impact of emergency in society. In particular, research behavior in crisis management is based on systematic and improvised activities directed to solve and/or constrain problems in a limited amount of time. In fact, in the initial phase of crisis management, research behavior is focused on the use of inventive analogies in the development of scientific research that can be helpful to support solutions that solve complex problems in the presence of environmental threats (Bonnardel, 2000). For instance, in the presence of COVID-19 pandemic crisis, scholars developed studies, in a perspective of analogical thinking, to apply Tocilizumab (a chronic inflammatory disorder in which the body's immune system attacks its joints, and it is one of the most common autoimmune diseases) to treat the respiratory and health disorders of COVID-19 (Ardito *et al.*, 2021). In addition, research behavior in crisis management, such as during COVID-19 pandemic, is mainly directed to achieve solutions [e.g., effective vaccines, new therapies, or other solutions] quickly (Coccia, 2021). In fact, accelerated rate of growth of crisis-driven research field of COVID-19 is supporting a scientific (and likely technological) paradigm shift to treat infectious diseases based on novel type of messenger RNA vaccines, known as mRNA vaccines for high levels of protection by preventing COVID-19 among people that are vaccinated. This new approach is different from classical approaches to vaccination because immunogenic proteins of a pathogen can be engineered into a non-pathogenic or attenuated vector that can incite the immune system similarly to a real infection (Smoot, 2020). Crisis-driven research field of COVID-19 has accelerated the transition towards these innovative types of mRNA vaccines and leading companies in pharmaceutical sector, such as AstraZeneca, Pfizer, Roche, etc. are now focusing human and economic resources on vectored, subunit, RNA, and DNA platforms, respectively. In addition, previous vaccines have been developed in about four years, the R&D of mRNA vaccines to cope with COVID-19 global pandemic has been less than one year after the discovery of the SARS-CoV-2; manifold public agencies for protecting and promoting public health through the control and supervision in the United Kingdom, the US, Europe and other countries confirm that mRNA vaccines for COVID-19 can be effective and safely tolerated in population (Abbasi, 2020; Coccia, 2021; Heaton, 2020; Jeyanathan *et al.*, 2020; Komaroff, 2020; Sanjay Mishra, 2020). Overall, then, crisis-driven research field of COVID-19 is generating a paradigm shift towards mRNA vaccines.

6. Conclusion and limitations

Social studies of science show that factors determining the evolution of research fields are due to endogenous factors in science, such as, *splitting* and

merging of social communities: splitting can account for branching mechanisms, such as specialization and fragmentation, while merging can capture the synthesis of new fields from old ones (Sun *et al.*, 2013). However, this study reveals that the evolution of research fields that can be also crisis-driven, such as the research field COVID-19 originated in 2019. In particular, relevant problems and environmental threats generated by unpredictable crisis can support the accelerated evolution of research fields characterized by continuous scientific advances directed to explain and solve unknown problems, support discoveries, and also scientific and technological paradigm shifts (cf., Becsei-Kilborn, 2010).

These conclusions are of course tentative. A limitation of this study is that sources under study may only capture certain aspects of the on-going dynamics of science a period of crisis. In addition, high production rate and publication frequency in the research field of COVID-19 can be also due to that in the presence of emergency, publications associated with COVID-19 have been published without formal procedures of publication. This fact may have increased publication frequency and control factors are necessary to consider in future development of this study. In fact, we know that other things are not equal in the dynamics of science over time and space. Therefore, the identification of general patterns and characteristics of science in the presence of social, economic and health crisis is a non-trivial exercise because society and as a consequence scientific results change rapidly under a social stress given by unforeseen shocks of global crises. To conclude, there is need for much more detailed research with additional data to clarify the relations and scientific change underlying the evolution of new scientific fields in the presence of crisis and environmental threats, such as considering collaboration intensity, openness, intellectual property rights, different sources/procedures of academic publications, different motivations associated with funding, etc.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. No funding was received for this study.

References

Abbasi, J. (2020). COVID-19 and mRNA vaccines-first large test for a new approach. *JAMA*, 324(12), 1125–1127. doi. 10.1001/jama.2020.16866

Ardito, L., Coccia, M., Messeni-Petruzzelli A. (2021). Technological exaptation and crisis management: Evidence from COVID-19 outbreaks. *R&D Management*, doi. 10.1111/radm.12455

Atlasi, R., Noroozi-Chakoli, A., Ramezani, A. *et al.* (2021). Scientometric analyzing the output of researchers and organizations on COVID-19 for better conducting the scientific efforts: with a glance to endocrinology. *J Diabetes Metab Disord*. doi. 10.1007/s40200-020-00718-7

Becsei-Kilborn, E. (2010). Scientific discovery and reputation: the reception of Peyton Rous' discovery of the chicken sarcoma virus. *Journal of the History of Biology*, 43, 111-157. doi. 10.1007/s10739-008-9171-y

Belli, S., Mugnaini, R., Baltà, J. *et al.* (2020). Coronavirus mapping in scientific publications: When science advances rapidly and collectively, is access to this knowledge open to society? Scientometrics 124, 2661–2685. https://doi.org/10.1007/s11192-020-03590-7

Bonnardel, N. (2000). Towards understanding and supporting creativity in design: analogies in a constrained cognitive environment. *Knowledge-Based Systems*, 13, 7, 505–513. doi. 10.1016/S0950-7051(00)00067-8

CDC, (2021). 2009 H1N1 pandemic (H1N1pdm09 virus), Accessed June 2021. [Retrieved from].

Coccia, M. (2001). Satisfaction, work involvement and R&D performance. *International Journal of Human Resources Development and Management*, 1(2-3-4), 268-282. doi. 10.1504/IJHRDM.2001.001010

Coccia, M. (2003). Metrics of R&D performance and management of public research institute. *Proceedings of IEEE- IEMC 03*, Piscataway, pp.231-236.

Coccia, M. (2004). Spatial metrics of the technological transfer: analysis and strategic management. *Technology Analysis & Strategic Management*, 16(1), 31-52. doi. 10.1080/0953732032000175490

Coccia, M. (2005). Countrymetrics: valutazione della performance economica e tecnologica dei paesi e posizionamento dell'Italia, *Rivista Internazionale di Scienze Sociali*, CXIII(3), 377-412.

Coccia, M. (2005a). Metrics to measure the technology transfer absorption: analysis of the relationship between institutes and adopters in northern Italy. *International Journal of Technology Transfer and Commercialization*, 4(4), 462-486. doi. 10.1504/IJTTC.2005.006699

Coccia, M. (2005b). Technometrics: Origins, historical evolution and new direction, *Technological Forecasting & Social Change*, 72(8), 944-979. doi. 10.1016/j.techfore.2005.05.011

Coccia, M. (2005c). Economics of scientific research: origins, nature and structure, *Proceedings of Economic Society of Australia*.

Coccia, M. (2006). Classifications of innovations: survey and future directions. *Working Paper Ceris del Consiglio Nazionale delle Ricerche*, 8(2), 1-19. [Retrieved from].

Coccia, M. (2006a). Analysis and classification of public research institutes. *World Review of Science, Technology and Sustainable Developmen*t, 3(1), 1-16.

Coccia, M. (2007). A new taxonomy of country performance and risk based on economic and technological indicators, *Journal of Applied Economics*, 10(1), 29-42.

Coccia, M. (2008). Science, funding and economic growth: analysis and science policy implications. *World Review of Science, Technology and Sustainable Development*, 5(1), 1-27. doi. 10.1504/WRSTSD.2008.01781

Coccia, M. (2008a). Spatial mobility of knowledge transfer and absorptive capacity: analysis and measurement of the impact within the geoeconomic space. *The Journal of Technology Transfer*, 33(1), 105-122. doi. 10.1007/s10961-007-9032-4

Coccia, M. (2008b). New organizational behaviour of public research institutions: Lessons learned from Italian case study. *International Journal of Business Innovation and Research*, 2(4), 402–419. doi. 10.1504/IJBIR.2008.018589

Coccia, M. (2009). A new approach for measuring and analyzing patterns of regional economic growth: empirical analysis in Italy. *Italian Journal of Regional Science- Scienze Regionali*, 8(2), 71-95. doi. 10.3280/SCRE2009-002004

Coccia, M. (2009a). Measuring the impact of sustainable technological innovation, *International Journal of Technology Intelligence and Planning*, 5(3), 276-288. doi. 10.1504/IJTIP.2009.026749

Coccia, M. (2010). Public and private R&D investments as complementary inputs for productivity growth. *International Journal of Technology, Policy and Management*, 10(1/2), 73-91. doi. 10.1504/IJTPM.2010.032855

Coccia, M. (2010a). Foresight of technological determinants and primary energy resources of future economic long waves, *International Journal of Foresight and Innovation Policy*, 6(4), 225–232. doi. 10.1504/IJFIP.2010.037468

Coccia, M. (2010b). Energy metrics for driving competitiveness of countries: Energy weakness magnitude, GDP per barrel and barrels per capita. *Energy Policy*, 38(3), 1330-1339. doi. 10.1016/j.enpol.2009.11.011

Coccia, M. (2010c). Spatial patterns of technology transfer and measurement of its friction in the geo-economic space. *International Journal of Technology Transfer and Commercialisation*, 9(3), 255-267. doi. 10.1504/IJTTC.2010.030214

Coccia, M. (2010d). The asymmetric path of economic long waves, *Technological Forecasting & Social Change*, 77(5), 730-738. doi. 10.1016/j.techfore.2010.02.003

Coccia, M. (2010e). Democratization is the driving force for technological and economic change, *Technological Forecasting & Social Change*, 77(2), 248-264. doi. 10.1016/j.techfore.2009.06.007

Coccia, M. (2011). The interaction between public and private R&D expenditure and national productivity. *Prometheus-Critical Studies in Innovation*, 29(2), 121-130. doi. 10.1080/08109028.2011.601079

Coccia, M. (2012). Political economy of R&D to support the modern competitiveness of nations and determinants of economic optimization and inertia, *Technovation*, 32(6), 370–379. doi. 10.1016/j.technovation.2012.03.005

Coccia, M. (2012a). Evolutionary trajectories of the nanotechnology research across worldwide economic players. *Technology Analysis & Strategic Management*, 24(10), 1029-1050. doi. 10.1080/09537325.2012.705117

Coccia, M. (2012b). Evolutionary growth of knowledge in path-breaking targeted therapies for lung cancer: radical innovations and structure of the new technological paradigm. *International Journal of Behavioural and Healthcare Research*, 3(3-4), 273-290. doi. 10.1504/IJBHR.2012.051406

Coccia, M. (2012c). Converging genetics, genomics and nanotechnologies for groundbreaking pathways in biomedicine and nanomedicine. *International Journal of Healthcare Technology and Management*, 13(4), 184-197. doi. 10.1504/IJHTM.2012.050616

Coccia, M. (2012d). Driving forces of technological change in medicine: Radical innovations induced by side effects and their impact on society and healthcare. *Technology in Society*, 34(4), 271-283. doi. 10.1016/j.techsoc.2012.06.002

Coccia, M. (2013). What are the likely interactions among innovation, government debt, and employment? Innovation: *The European Journal of Social Science Research*, 26(4), 456–471. doi. 10.1080/13511610.2013.863704

Coccia, M. (2013a). The effect of country wealth on incidence of breast cancer. *Breast Cancer Research and Treatment*, 141(2), 225-229. doi. 10.1007/s10549-013-2683-y

Coccia, M. (2014). Path-breaking target therapies for lung cancer and a far-sighted health policy to support clinical and cost effectiveness. *Health Policy and Technology*, 1(3), 74-82. doi. 10.1016/j.hlpt.2013.09.007

Coccia, M. (2014a). Emerging technological trajectories of tissue engineering and the critical directions in cartilage regenerative medicine. *Int. J. Healthcare Technology and Management*, 14(3), 194-208. doi. 10.1504/IJHTM.2014.064247

Coccia, M. (2014b). Converging scientific fields and new technological paradigms as main drivers of the division of scientific labour in drug discovery process: the effects on strategic management of the R&D corporate change. *Technology Analysis & Strategic Management*, 26(7), 733-749, doi. 10.1080/09537325.2014.882501

Coccia, M. (2014c). Driving forces of technological change: The relation between population growth and technological innovation-Analysis of the optimal interaction across countries, *Technological Forecasting & Social Change*, 82(2), 52-65. doi. 10.1016/j.techfore.2013.06.001

Coccia, M. (2014). Socio-cultural origins of the patterns of technological innovation: What is the likely interaction among religious culture, religious plurality and innovation? Towards a theory of socio-cultural drivers of the patterns of technological innovation, *Technology in Society*, 36(1), 13-25. doi. 10.23760/2421-7158.2017.004

Coccia, M. (2014e). Religious culture, democratisation and patterns of technological innovation. *International Journal of Sustainable Society*, 6(4), 397-418. doi. 10.1504/IJSSOC.2014.066771

Coccia, M. (2014f). Structure and organisational behaviour of public research institutions under unstable growth of human resources, *Int. J. Services Technology and Management*, 20(4/5/6), 251–266. doi. 10.1504/IJSTM.2014.068857

Coccia, M. (2014g). Steel market and global trends of leading geo-economic players. International *Journal of Trade and Global Markets*, 7(1), 36-52, doi. 10.1504/IJTGM.2014.058714

Coccia, M. (2015). The Nexus between technological performances of countries and incidence of cancers in society. *Technology in Society*, 42, 61-70. doi. 10.1016/j.techsoc.2015.02.003

Coccia, M. (2015a). Patterns of innovative outputs across climate zones: the geography of innovation, *Prometheus. Critical Studies in Innovation*, 33(2), 165-186. doi. 10.1080/08109028.2015.1095979

Coccia, M. (2015b). General sources of general purpose technologies in complex societies: Theory of global leadership-driven innovation, warfare and human development, *Technology in Society*, 42, 199-226. doi. 10.1016/j.techsoc.2015.05.008

Coccia, M. (2015c). Spatial relation between geo-climate zones and technological outputs to explain the evolution of technology. *Int. J. Transitions and Innovation Systems*, 4(1-2), 5-21. doi. 10.1504/IJTIS.2015.074642

Coccia, M. (2015d). Technological paradigms and trajectories as determinants of the R&D corporate change in drug discovery industry. *International Journal Knowledge and Learning*, 10(1), 29-43. doi. 10.1504/IJKL.2015.071052

Coccia, M. (2016). Asymmetric paths of public debts and of general government deficits across countries within and outside the European monetary unification and economic policy of debt dissolution. *The Journal of Economic Asymmetries*, 15, 17-31. doi. 10.1016/j.jeca.2016.10.003

Coccia, M. (2016a). Radical innovations as drivers of breakthroughs: characteristics and properties of the management of technology leading to superior organizational performance in the discovery process of R&D labs. *Technology Analysis & Strategic Management*, 28(4), 381-395. doi. 10.1080/09537325.2015.1095287

Coccia, M. (2016). Problem-driven innovations in drug discovery: co-evolution of radical innovation with the evolution of problems, *Health Policy and Technology*, 5(2), 143-155. doi. 10.1016/j.hlpt.2016.02.003

Coccia, M. (2016c). The relation between price setting in markets and asymmetries of systems of measurement of goods. *The Journal of Economic Asymmetries*, 14(B), 168-178. doi. 10.1016/j.jeca.2016.06.001

Coccia, M. (2017). The source and nature of general purpose technologies for supporting next K-waves: Global leadership and the case study of the U.S. Navy's Mobile User Objective System, *Technological Forecasting and Social Change*, 116, 331-339. doi. 10.1016/j.techfore.2016.05.019

Coccia, M. (2017a). Optimization in R&D intensity and tax on corporate profits for supporting labor productivity of nations. *The Journal of Technology Transfer*, doi. 10.1007/s10961-017-9572-1

Coccia, M. (2017b). Varieties of capitalism's theory of innovation and a conceptual integration with leadership-oriented executives: the relation between typologies of executive, technological and socioeconomic performances. *Int. J. Public Sector Performance Management*, 3(2), 148–168. doi. 10.1504/IJPSPM.2017.084672

Coccia, M. (2017c). Sources of disruptive technologies for industrial change. *L'industria –rivista di Economia e Politicaindustriale*, 38(1), 97-120.
Coccia, M. (2017d). Sources of technological innovation: Radical and incremental innovation problem-driven to support competitive advantage of firms. *Technology Analysis & Strategic Management*, 29(9), 1048-1061. doi. 10.1080/09537325.2016.1268682
Coccia, M. (2017e). A Theory of general causes of violent crime: Homicides, income inequality and deficiencies of the heat hypothesis and of the model of CLASH, *Aggression and Violent Behavior*, 37, 190-200. doi. 10.1016/j.avb.2017.10.005
Coccia, M. (2017f). New directions in measurement of economic growth, development and under development, *Journal of Economics and Political Economy*, 4(4), 382-395.
Coccia, M. (2017g). Disruptive firms and industrial change, *Journal of Economic and Social Thought*, 4(4), 437-450.
Coccia, M. (2017h). The Fishbone diagram to identify, systematize and analyze the sources of general purpose Technologies, *Journal of Social and Administrative Sciences*, 4(4), 291-303.
Coccia, M. (2018). A theory of the general causes of long waves: War, general purpose technologies, and economic change. *Technological Forecasting & Social Change*, 128, 287-295 10.1016/j.techfore.2017.11.013
Coccia, M. (2018a). The relation between terrorism and high population growth, *Journal of Economics and Political Economy*, 5(1), 84-104.
Coccia, M. (2018c). Violent crime driven by income Inequality between countries, *Turkish Economic Review*, 5(1), 33-55.
Coccia, M. (2018d). The origins of the economics of innovation, *Journal of Economic and Social Thought*, 5(1), 9-28.
Coccia, M. (2018e). Theorem of not independence of any technological innovation, *Journal of Economics Bibliography*, 5(1), 29-35.
Coccia, M. (2018e). Theorem of not independence of any technological innovation, *Journal of Social and Administrative Sciences*, 5(1), 15-33.
Coccia, M. (2018f). Competition between basic and applied research in the organizational behaviour of public research labs, *Journal of Economics Library*, 5(2), 118-133.
Coccia, M. (2018g). An introduction to the methods od inquiry in social sciences, *Journal of Social and Administrative Sciences*, 5(2), 116-126.
Coccia, M., & Bellitto, M. (2018). Human progress and its socioeconomic effects in society, *Journal of Economic and Social Thought*, 5(2), 160-178.
Coccia, M., & Igor, M. (2018). Rewards in public administration: a proposed classification, *Journal of Social and Administrative Sciences*, 5(2), 68-80.
Coccia, M., & Bozeman, B. (2016). Allometric models to measure and analyze the evolution of international research collaboration. *Scientometrics*, 108(3), 1065-1084. doi. 10.1007/s11192-016-2027-x
Coccia, M., Falavigna, G., & Manello, A. 2015. The impact of hybrid public and market-oriented financing mechanisms on scientific portfolio and performances of public research labs: a scientometric analysis. Scientometrics, 102(1), 151-168. doi. 10.1007/s11192-014-1427-z
Coccia, M., & Finardi, U. (2012). Emerging nanotechnological research for future pathway of biomedicine. *International Journal of Biomedical Nanoscience and Nanotechnology*, 2(3-4), 299-317. doi. 10.1504/IJBNN.2012.051223
Coccia, M., & Finardi, U. (2013). New technological trajectories of non-thermal plasma technology in medicine. *International Journal of Biomedical Engineering and Technology*, 11(4), 337-356. doi. 10.1504/IJBET.2013.055665
Coccia, M., Finardi, U., & Margon, D. (2012). Current trends in nanotechnology research across worldwide geo-economic players, *The Journal of Technology Transfer*, 37(5), 777-787. doi. 10.1007/s10961-011-9219-6
Coccia, M., & Rolfo, S. (2000). Ricerca pubblica e trasferimento tecnologico: il caso della regione Piemonte. *In* S. Rolfo (ed), *Innovazione e piccole imprese in Piemonte*, Franco Angeli Editore, Milano.

Coccia, M., & Rolfo, S. (2002). Technology transfer analysis in the Italian national research council, Technovation - *The International Journal of Technological Innovation and Entrepreneurship*, 22(5), 291-299. doi. 10.1016/S0166-4972(01)00018-9

Coccia, M., & Rolfo, S. (2007). How research policy changes can affect the organization and productivity of public research institutes, *Journal of Comparative Policy Analysis, Research and Practice*, 9(3) 215-233. doi. 10.1080/13876980701494624

Coccia, M., & Rolfo, S. (2010). New entrepreneurial behaviour of public research organizations: opportunities and threats of technological services supply, *International Journal of Services Technology and Management*, 13(1-2), 134-151. doi. 10.1504/IJSTM.2010.029674

Coccia, M., & Rolfo, S. (2013). Human resource management and organizational behavior of public research institutions, *International Journal of Public Administration*, 36(4), 256-268. doi. 10.1080/01900692.2012.756889

Coccia, M., & Rolfo, S. (2009). Project management in public research organization: Strategic change in complex scenarios. International Journal of Project Organisation and Management, 1(3), 235–252. doi. 10.1504/IJPOM.2009.027537

Coccia, M., & Wang, L. (2015). Path-breaking directions of nanotechnology-based chemotherapy and molecular cancer therapy, *Technological Forecasting and Social Change*, 94, 155–169. doi. 10.1016/j.techfore.2014.09.007

Coccia, M., & Wang, L. (2016). Evolution and convergence of the patterns of international scientific collaboration. *Proceedings of the National Academy of Sciences of the United States of America*, 113(8), 2057-2061. doi. 10.1073/pnas.1510820113

De Roeck, A. (2016). The probability of discovery, *Technol. Forecast. Soc. Change*, 112, 13-19. doi. 10.1016/j.techfore.2016.04.020

Decramer, M., Cooper, C.B. (2010). Treatment of COPD: the sooner the better? Thorax; 65:837e841. doi. 10.1136/thx.2009.133355

del Rio-Chanona, R.M., Mealy, P., Pichler, A., Lafond, F., & Farmer, D. (2020). Supply and demand shocks in the COVID-19 pandemic: An industry and occupation perspective; 2020. [Retrieved from].

Di Girolamo, N., Meursinge Reynders, R. (2020). Characteristics of scientific articles on COVID-19 published during the initial 3 months of the pandemic. *Scientometrics*, 125, 795–812. doi. 10.1007/s11192-020-03632-0

Dos Santos, W.G. (2020). Natural history of COVID-19 and current knowledge on treatment therapeutic options. *Biomedicine & pharmacotherapy = Biomedecine & pharmacotherapie*, 129, 110493. doi. 10.1016/j.biopha.2020.110493

Ebadi, A., Xi, P., Tremblay, S., Spencer, B., Pall, R., & Wong, A. (2020). Understanding the temporal evolution of COVID-19 research through machine learning and natural language processing. Scientometrics, 1–15. Advance online publication. doi. 10.1007/s11192-020-03744-7

Fanelli, D., & Glänzel, W. (2013). Bibliometric evidence for a hierarchy of the sciences. *PLoSONE*, 8(6), e66938. doi. 10.1371/journal.pone.0066938

Fortunato, S., Bergstrom, C.T., Börner, K., Evans, J.A., Helbing D., Milojević, S., Petersen, A. M., Radicchi F., Sinatra R., Uzzi B., Vespignani A., Waltman L., Wang D., & Barabási A.-L. (2018). Science of science. *Science*, 359(6379). doi. 10.1126/science.aao0185

Gibbons, M., Limoges, C., Nowotny, H., Schwatzman, S., Scott, P., & Trow, M. (1994). *The New Production of Knowledge: the Dynamics of Science and Research in Contemporary Society*. Sage Publications, London.

Guerrieri, V., Lorenzoni, G., Straub, L., & Werning, I. (2020). Macroeconomic implications of COVID-19: Can negative supply shocks cause demand shortages? *NBER Working Paper*, No.26918. doi. 10.3386/w26918 .

Haghani, M., & Bliemer, M. (2020). Covid-19 pandemic and the unprecedented mobilisation of scholarly efforts prompted by a health crisis: Scientometric comparisons across SARS, MERS and 2019-nCoV literature. Scientometrics, 1–32. doi. 10.1007/s11192-020-03706-z

Halbert, R.J., Natoli, J.L., Gano, A., Badamgarav, E., Buist, A.S., & Mannino D.M. (2006). Global burden of COPD: systematic review and meta-analysis, *Eur. Respir. J.* 28, 523–532.

Heaton, P.M. 2020. The Covid-19 vaccine-development multiverse. *The New England Journal of Medicine*, 383(20), 1986–1988. doi. 10.1056/NEJMe2025111

Jeyanathan, M., Afkhami, S., Smaill, F., Miller, M.S., Lichty, B.D., & Xing, Z. (2020). Immunological considerations for COVID-19 vaccine strategies. *Nat Rev Immunol.* 20(10), 615-632. doi. 10.1038/s41577-020-00434-6

Kealey, T. (1996). *The Economic Laws of Scientific Research*. MacMillan Press, London.

Komaroff, A. (2020). Why are mRNA vaccines so exciting? *Harvard Health Blog,* Posted December 10, 2020, 2:30 pm, Updated December 18, 2020, 7:52 pm. [Retrieved from].

Kuhn, T.S. (1996). *The Sstructure of Scientific Revolutions*. University of Chicago Press.

Lange, P., Celli B., Agustí A., Boje Jensen G., Divo M., Faner R., Guerra S., Marott J.L., Martinez F.D., Martinez-Camblor P., Meek P., Owen C.A., Petersen H., Pinto-Plata V., Schnohr P., Sood A., Soriano J. B., Tesfaigzi Y., Vestbo J. (2015). Lung-Function Trajectories Leading to Chronic Obstructive Pulmonary Disease. *The New England journal of Medicine*, 373(2), 111–122. doi. 10.1056/NEJMoa1411532

National Cancer Institute, (2021). About cancer. accessed 6th January 2021. [Retrieved from].

Pal, J.K. (2021). Visualizing the knowledge outburst in global research on COVID-19. *Scientometrics* 2021. 10.1007/s11192-021-03912-3

Price de Solla, D.J. (1986). *Little Science, Big Science...and Beyond*. Columbia University Press, NY.

Sachini, E., Sioumalas-Christodoulou, K., Chrysomallidis, C. *et al.* (2021). COVID-19 enabled co-authoring networks: a country-case analysis. *Scientometrics*. doi. 10.1007/s11192-021-03952-9

Sanjay M. (2020). How mRNA vaccines from Pfizer and Moderna work, why they're a breakthrough and why they need to be kept so cold. Vanderbilt University Medical Center, Vanderbilt University. November 18, 2020 1.19pm GMT. [Retrieved from].

Scopus, (2021). Document Search, Document. Article title, Abstract, Keywords. Accessed from 1st April to 31 December 2020 and 1st January to 6 June 2021. [Retrieved from].

Sepkowitz, K.A. (2001). AIDS – the first 20 years. *The New England Journal of Medicine*. 344(23), 1764–72. doi. 10.1056/NEJM200106073442306

Siafakas, N., Bizymi, N., Mathioudakis, A., & Corlateanu, A. (2018). EARLY versus MILD Chronic Obstructive Pulmonary Disease (COPD). *Respiratory Medicine*, 140, 127–131. doi. 10.1016/j.rmed.2018.06.007

Smoot, J. (2020). Classic and new technologies vying to be the first COVID-19 vaccine. Posted June 11, 2020. [Retrieved from].

Sun X., Kaur, J., Milojevic´ S., Flammini A., & Menczer, F. (2013). Social Dynamics of Science. *Scientific Reports*, 3(1069), 1-6, doi. 10.1038/srep01069

WHO, (2021). Middle East respiratory syndrome coronavirus (MERS-CoV). accessed June 2021. [Retrieved from].

WHO, (2021a). Zika virus, accessed June 2021. [Retrieved from].

Xu, H., Winnink, J., Yue, Z., Zhang, H., & Pang, H. (2021). Multidimensional Scientometric indicators for the detection of emerging research topics, *Technological Forecasting and Social Change*, 163. doi. 10.1016/j.techfore.2020.120490

Zhang, L., Zhao, W., Sun, B., Huang, Y., & Glänzel W. (2020). How scientific research reacts to international public health emergencies: a global analysis of response patterns. *Scientometrics*, 1–27. doi. 10.1007/s11192-020-03531-4