Understanding COVID-19 diffusion requires an interdisciplinary, multi-dimensional approach

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A B S T R A C T

After COVID-19 initial diffusion in Europe in March 2020, research has suggested a direct correlation between environmental pollution and contagion dynamics (i.e., environment-to-human pollution), thereby indicating that mechanisms other than human-to-human transmission can explain COVID-19 diffusion. However, these studies did not consider that complex outcomes, such as a pandemic's diffusion patterns, are typically caused by a multiplicity of environmental, economic and social factors. While disciplinary specialties increase scholars' attitudes of concentrating on specific factors, neglecting this multiplicity during a pandemic crisis can lead to misleading conclusions. This communication aims to focus on certain limitations of current research about environmental-to-human COVID-19 transmission and shows the benefit of an interdisciplinary, multi-dimensional approach to understand the geographical diversity of contagion diffusion patterns.

1. Introduction

After the first detected cases in Wuhan, China at the end of 2019, the COVID-19 pandemic was officially declared on January 30, 2020, opening an unexpected global sanitary crisis which has hit our economies and societies. While at the end of February 2020 only Italy was showing high contagion numbers in Europe, in two months the pandemic eventually diffused in almost all the world's regions.

Fig. 1 shows the diffusion of COVID-19 on May 17, 2020 (data were published by the European Centre for Disease Prevention and Control). The majority of COVID-19 infected cases were detected in North America and Europe. While the pattern of COVID-19 diffusion in Italy, Spain, France, and Grain Britain has been similar, yet delayed a few weeks, the virus diffusion in other continents, e.g., Europe and USA vs. Africa and Asia, was different. These country differences have motivated scholars in trying to find the key variables to explain the different diffusion rates, although the crucial role of time delays was often neglected. In March 2020, when Italy still was the most affected country in Europe, several studies suggested a direct correlation between environmental pollution and virus diffusion (defined as environment-to-human pollution), thereby indicating that mechanisms other than human-to-human transmission could explain the observed COVID-19 diffusion patterns. In particular, the prevalence of the contagious diffusion in Northern Italy (in particular in Lombardia), which generally

suffers of bad air quality, fueled debate about the possible role of airborne particulate matter (PM) on COVID-19 spread. In particular, some researchers associated the Italian situation to Wuhan, due to China well-reported air conditions (Sterpetti, 2020, in press).

Indeed, COVID-19 infection can cause pneumonia and acute respiratory syndrome, i.e., symptoms that can be exacerbated by air pollution. Although not directly connected to COVID-19 diffusion, previous research has suggested a correlation between poor air quality and development and worsening of chronic inflammatory disease (Alves et al., 2018). Since COVID-19 is mainly a respiratory syndrome, polluted air was supposed to increase the risk of death of infected patients, mainly due to the high concentrations of airborne PM (Paital, 2020, in press). These studies used these findings to explain the difference in the mortality rate in EU countries, e.g., the high population mortality in Northern Italy (Conticini et al., 2020).

On the other hand, research has considered other important environmental effects on the propagation of COVID-19 infection (i.e., environment-to-human pollution). For instance, while certain authors have proposed that geo-environmental determinants (such as PM) could accelerate COVID-19 diffusion (Coccia, 2020), others have suggested that PM could act as virus carrier, thus explaining so higher infections in areas with higher PM concentration (Setti et al., 2020) (Del Buono et al., 2020).

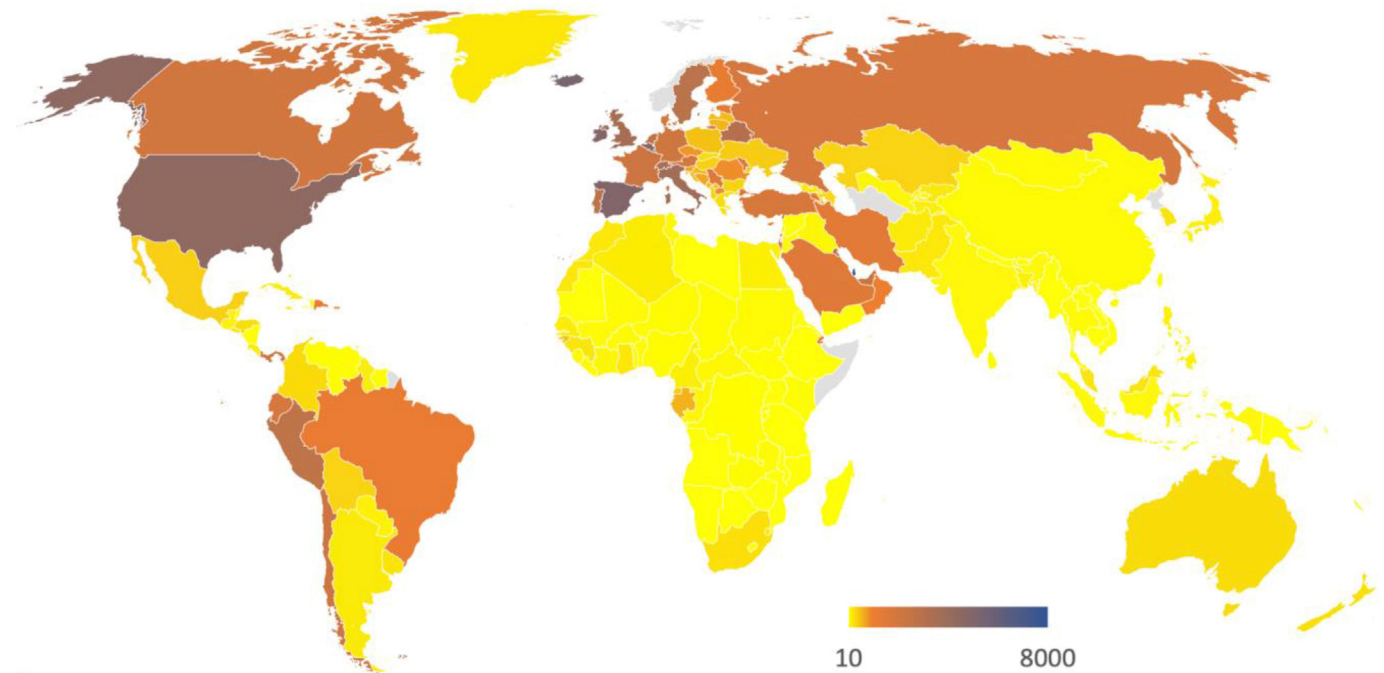However, environmental-to-human transmission is a complex,

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Fig. 1. Total detected COVID-19 infection cases on May 17, 2020 reported per million people (published by the European Centre for Disease P.

multi-layered process, which requires considering possible overlapping variables of various nature other than only environmental ones. Excluding a comprehensive look at these various variables can help research achieve at best suggestive correlations, certainly not causal links. Overcoming the "correlation fallacy" requires integrating micro and macro levels of analysis to search for fundamental generative mechanisms of complex aggregate patterns (Manicas, 2006). When this is not done, as in the vast literature on the environment-to-human transmission mechanisms of COVID-19, research confuses effects and correlations and, in this case, attributes explanatory power to environmental issues ignoring other relevant factors (Bontempi, in press).

There is consensus on the fact that virus diffusion is mainly due to human interactions. Nonetheless, given that considering these variables in current models is difficult, any possible indicator reflecting human-to-human transmission is substantially neglected in current research concerning environmental-to-human transmission of COVID-19 (Bavel et al., 2020). This has problematic implications as any analysis claiming to find strong correlations without considering human-to-human transmission could not establish any robust causal explanation.

This communication aims to look at certain limitations of previous research on environmental-to-human transmission mechanisms of COVID-19 and proposes an interdisciplinary vision to look at factors previously underestimated. In particular, we consider certain economic variables (i.e., human-to-human transmission), which could be viewed as a proxy of population mobility and social interaction (Ahmadi et al., 2020). This communication aims to highlight certain limitations of previous research but also to show that research on COVID-19 diffusion patterns must consider a multiplicity of transmission channels, including environmental-to-human and human-to-human ones.

While it is difficult to measure social interaction at the microscopic level of each person-to-person contact, social interaction leaves aggregate traces in various databases regularly measuring economic activities. We argue that these factors can explain the initial diffusion of COVID-19, whereas other factors, such as the efficacy of mitigation measures and the quality of health care systems' responses, should be considered to explain later stages of COVID-19 diffusion and its impact on the number of infected cases and dead people.

1.1. Current limitations of COVID-19 research

Performing rigorous research on a complex global pandemic is problematic for several reasons, such as public pressure for immediate responses, misplaced expectations about the role of science, misunderstanding about the certainty of scientific knowledge, and confusion concerning public responsibility (Squazzoni et al., 2020). First, research is often limited to a specific field, e.g., health, environmental or economic factors, and scholars are blinded by excessive disciplinary specialization, which has shortcomings even in less critical conditions than a pandemic disease (Klein, 1990). While pandemics require global multi- and interdisciplinary approaches, we all are penalized by different disciplinary grammars leading specialists to attribute different meanings to the same concept (Bontempi, in press). To tackle the challenge of a pandemic, collaborative approaches are needed that help single specialists or mono-disciplinary teams to overcome their limits. Secondly, whenever a model is proposed to explain a global pandemic diffusion, its parameters must be clearly calibrated, different boundary conditions must be explored, and suitable reference areas must be considered. For instance, comparing the same variables while changing the selected area or separating, for example, a reference area with different virus diffusion rates, is key to evaluate the effect of a model's investigated parameters (Bontempi, 2020). While several studies recently looked at geographic comparisons between cities or countries, none examined significant association within cities or countries. For an association to be valid, it must be possibly observed both between and within geographic areas. This is fundamental to test the real incidence of the proposed parameters on the variability of virus diffusion rates.

Furthermore, developing a comprehensive vision of COVID-19 contagion requires more variables than usual research. Current findings on COVID-19 contagion could be penalized by lack of necessary data and variables. In order to examine COVID-19 contagion, there is need for parameters, such as the previous level (often undetected) of infected people, the density and mobility of population, the distance from the outbreak epicenter and the existence of a subway (able to accelerate the virus diffusion), to name a few, before the introduction of lock-down measures (Liu, 2020). The adoption of lock-down measures at different times has changed the dynamics of contagion. Unfortunately, these

factors are not sufficiently considered in current research. For instance, when estimating the different rates in contagion dynamics, a population's compliance with introduced measures to limit the diffusion, e.g., social distancing, and personal hygiene indicators, e.g., hand wash needs, are often not considered. This may lead to misplaced, even dangerous conclusions when countries where measures of lockdown were extremely severe like China are compared to Europe and some African countries, where these same measures were relatively loose.

Finally, time matters especially to assess the unfolding dynamics of contagion. For instance, some studies were performed at the beginning of COVID-19 diffusion in Europe and compared different regions on absolute numbers of confirmed cases, without considering the different temporal patterns in different counties (Ogen, 2020). Once the pandemic developed, estimations benefitted from more complete data and the fact that the disease was evenly spread across each country became evident. This also means that pandemic models must be adaptive, possibly with easy and quick updates as soon as new data can be included (Klein, 1990).

In this context, even considering only one of the most important environmental factors affecting COVID-19 diffusion, such as air pollution due to PM, requires a more complex vision. For instance, Fig. 2 reports the world $PM_{2.5}$ mean annual exposure (in micrograms per cubic meter) for 2017. Data were extracted from World Development Indicators Databank (https://www.worldbank.org/), choosing the last available data series. However, while PM mean concentrations were generally declining in Europe and USA in the last years, in most African and Asian countries values are still critical. Then, it is likely that the current air quality situations are similar (or better) in Europe and the United States.

A global analysis about $PM_{2.5}$ exposition highlights a critical situation in most of the world's developing countries. Countries with the highest $PM_{2.5}$ mean annual concentrations are Niger (94,0 µg/m^3), India (90,9 µg/m^3), Saudi Arabia (87,9 µg/m^3), Egypt (87 µg/m^3), and Cameron (72,8 µg/m^3). Among the less polluted area, there are countries like Finland (5,9 µg/m^3), Sweden (6,1 µg/m^3), Portugal (8,1 µg/m^3), Ireland (8,2 µg/m^3), Spain (9,7 µg/m^3), and United Kingdom (10,5 µg/m^3).

Let us now compare data about $PM_{2.5}$ mean concentrations worldwide with data about virus diffusion (see Figs. 1 and 2). A first comparison shows that outcomes are inconsistent: COVID-19 infections were higher in areas with better air conditions (such as Ireland, Spain, and United Kingdom). On the contrary, African countries and India, which present a high $PM_{2.5}$ pollution, were less affected (note that data about contagious are reported for May 17, 2020). This suggests that air quality (i.e., $PM_{2.5}$ concentration at world level) seems not being substantially influential on COVID-19 diffusion (Fig. 1), as already reported by previous research (Mollalo, 2020). This implies that geographical limitation of some analysis needs to be carefully considered in future studies.

On the other hand, research on air quality and COVID-19 can has a fundamental limitation: available data (Fig. 2) are reported as mean values at the country level, whereas local variations within each single country should be considered. However, in case of Italy, data about $PM_{2.5}$ concentration in 2017, available by ISPRA (http://www.isprambiente.gov.it/it) showed that the Italian mean annual exposure value of 16,7 µg/m^3, corresponds to a maximum value of 34 µg/m^3 and 33 µg/m^3 for the cities of Padova (Veneto) and Torino (Piemonte) respectively, which did not present significant critical patterns in terms of virus diffusion. This suggests that the most polluted Italian cities generally have better air quality (considering $PM_{2.5}$) than several countries, such as India (90,9 µg/m^3), Egypt (87,0 µg/m^3), Libya (54,2 µg/m^3), Algeria (38,9 µg/m^3), Bosnia and Herzegovina (27,7 µg/m^3), Macedonia (29,7 µg/m^3), Lebanon (30,6 µg/m^3), among others, which showed a limited COVID-19 contagion.

While further research is needed to examine the (lack of) interaction of air quality and virus diffusion in more detail, these examples suggest to expand the spectrum of possible environmental factors which could have an influence on virus diffusion. For instance, previous research proposed to consider climate conditions: higher temperature and humidity may reduce the strength of the virus and so decrease its persistence on objects (Neher et al., 2020), while Chin et al. (2020) suggested a negative correlation between temperature and virus diffusion, thereby explaining why certain countries such as India (with the 2nd highest population status) could have a delayed infection (Paital,
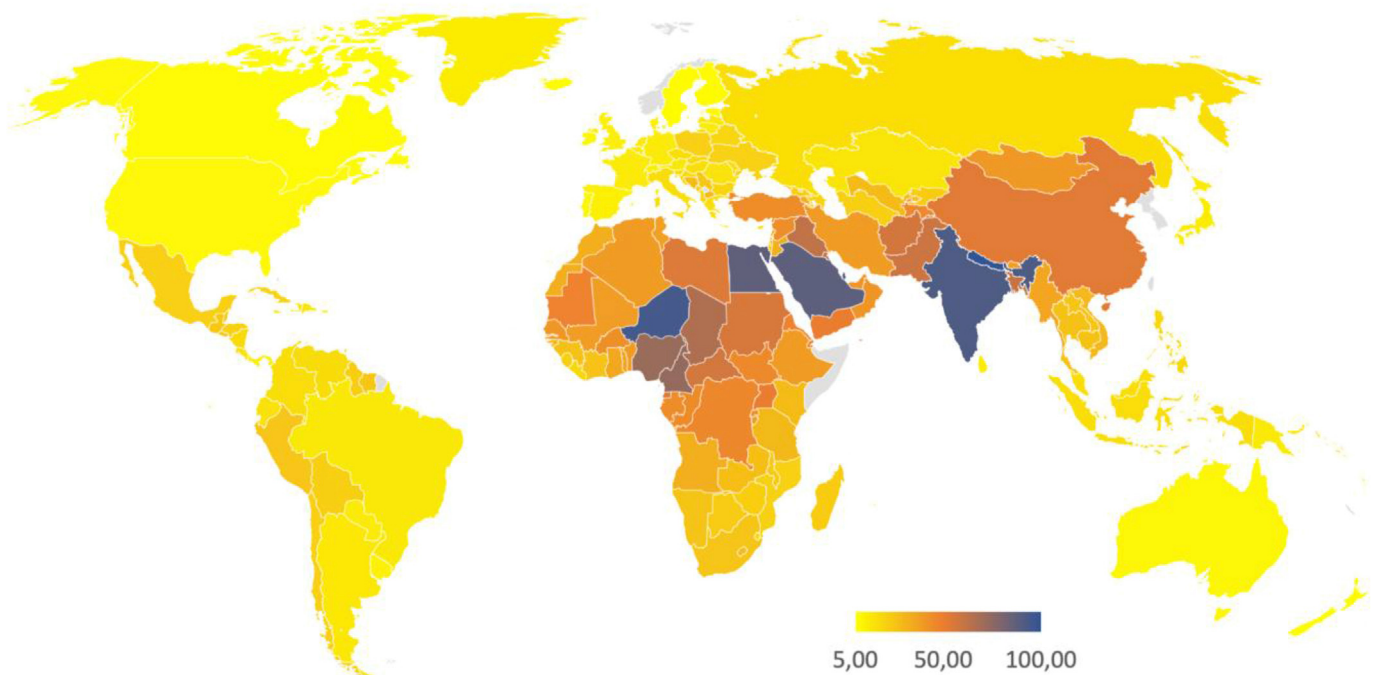

Fig. 2. World $PM_{2.5}$ mean annual exposure (in micrograms per cubic meter) for 2017. Data were downloaded from World Development Indicators Databank (https://www.worldbank.org/).
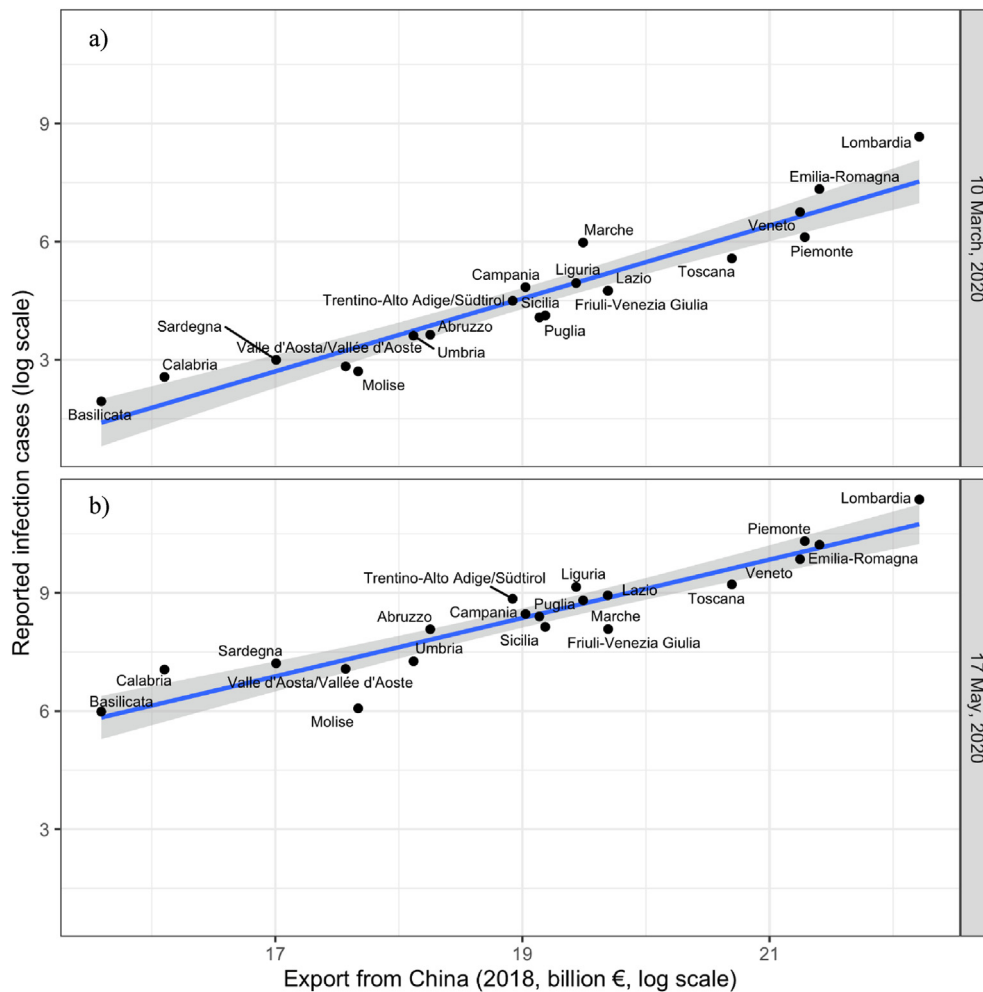
Fig. 3. The (logarithm of) number of COVID-19 cases in all Italian regions on March 10, 2020 (a) and May 17, 2020 (b) versus (logarithm of) the value of exports from China (data from ISTAT 2018), the country in which the infection originated.

2020). This suggests that research considering a variety of environmental factors is needed to establish whether pollution sources could be considered as spread determinants (i.e., in the environment-to-human pollution mechanisms study).

1.2. Understanding virus diffusion requires expanding our analysis to other factors

It was recently shown that interdisciplinary research is better suited to explore certain new parameters that could be relevant to explain the COVID-19 initial diffusion state (Bontempi, in press), such as economic connections between the infected areas. Commercial relationships require communication and intense social interaction among individuals, as well as persistent mobility patterns across areas, mostly related to the globalization of companies' value chains and markets. While it is difficult to map social networks, it is probable that a good measure of human-to-human initial virus diffusion mechanisms could be found in international trade.

Considering that there is inequality and heterogeneity in international trade relationships, fine-grained data at least at regional level should be considered. Indeed, it was recently shown that considering commercial trade (Bontempi, in press) of different regions (e.g., in Italy) is key to reveal a high correlation between the COVID-19 diffusion patterns in different areas.

Another recent model adapted to urban settings revealed that the distance from the first contagious area is negatively linked to the spread

of COVID-19 (Liu, 2020). It also suggested that subway, wastewater and residential garbage were positively related to the virus transmission. Recent research also reported that outdoor activities may reduce the possibility of virus diffusion, thereby suggesting that people's confinement in closed spaces, e.g., homes, could make them more susceptible to the infection (Holtmann et al., 2020); in particular, despite air pollution, a negative correlation was found between virus diffusion in China and the presence of green open spaces in urban settings (Liu, 2020), supporting the idea that the primary contagious sources happen indoor (human-to-human transmission).

To complicate the picture, virus diffusion is also influenced by country-specific imposed restrictions lock-down measures and, in particular, home confinement and reduced mobility have contributed to contain virus diffusion in some countries, thereby reducing the pace and extent of the expected COVID-19 impact. While limitations are very effective when the population density is high, population density parameters have been rarely considered in COVID-19 research. However, the importance of population density can be recognized by considering Mongolia's measures: despite its proximity to China and the mean $PM_{2.5}$ concentration of 41,1 μg/m^3 (higher than the value of most Northern Italy cities), the population density of 2 people for square kilometers of land area has probably limited the COVID-19 spread in this country (see Fig. 1).

Previous research has proposed that the highest number of cases of infection detected in large cities can be attributed to their destination for job seekers and investors (Auler et al., 2020; Tosepu et al., 2020).
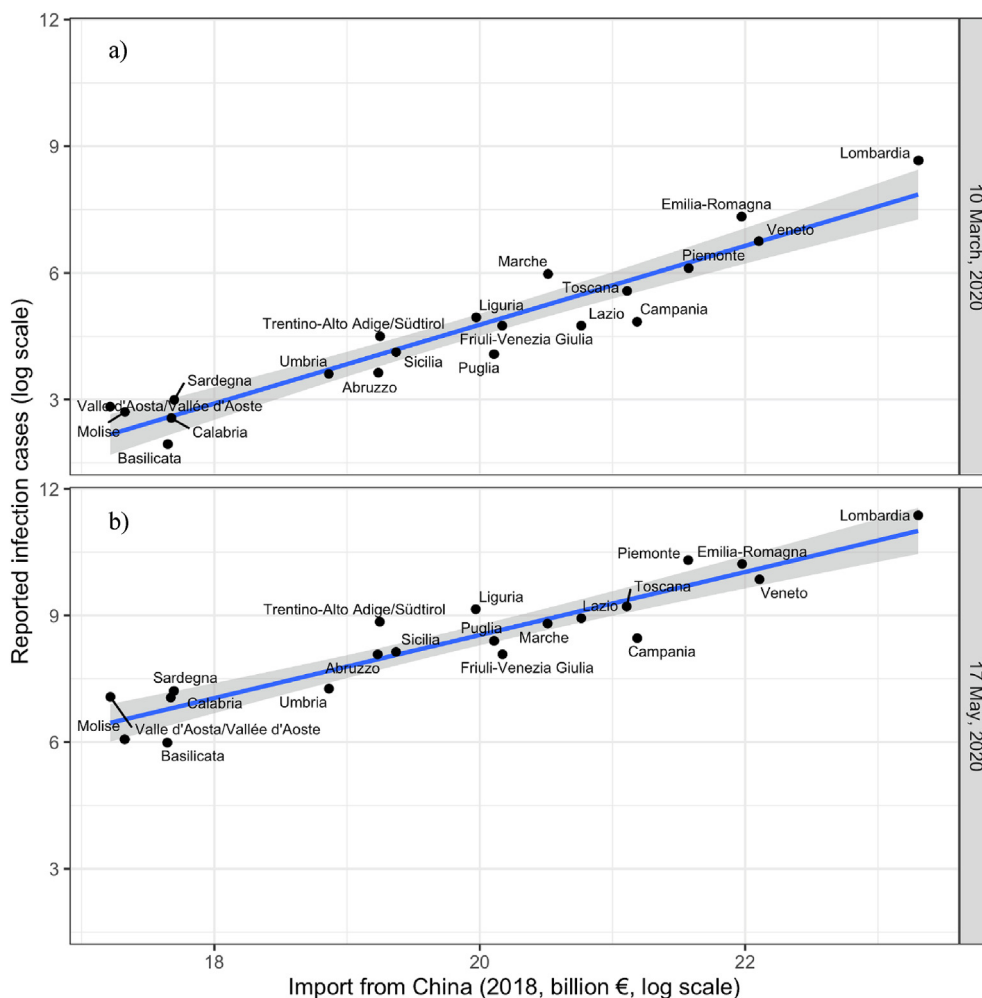
Fig. 4. The (logarithm of) number of COVID-19 cases in all Italian regions on March 10, 2020 (a) and May 17, 2020 (b) versus (logarithm of) the value of import from China (data from ISTAT 2018), the country in which the infection originated.

This suggests a possible relationship between contagion and certain economic preconditions. It is probable that countries at the frontline of the globalized economy (see supporting Fig. S1) and with denser import/export relationships with China could show higher initial values of contagion due to population mobility and social interaction. The hypothesis is that commercial trade could be a synthetic expression of higher social relationships created by economic activities: the greater the trade, the higher the exchanges and human contacts due to business collaboration, production coordination, and exchange of products.

Figs. 3 and 4 report data (from ISTAT - i.e. the National Institute of Statistics) about import and export with China, the country in which the infection originated, for all the Italian regions (data are from 2018, the last available data series). Fig. 3 shows a scatter plot of (logarithm of) the number of COVID-19 cases and (logarithm of) the value of exports from China, on 10th March and 17th May for all Italian regions (i.e., at the beginning and a later stage of the pandemic). The graph shows that in regions where trade values were higher, the number of contagions were higher, too. Note that the regions with the highest exports were in order: Lombardy, Emilia Romagna, Veneto and Piedmont. The order of contagions on 17th May showed Lombardy with the highest numbers, followed by Piedmont, Emilia Romagna and Veneto respectively. Fig. 4 shows the number of COVID cases (reported in logarithm) and the (logarithm of) value of import from China. This suggests that economic factors could explain the initial rate of infection, probably due to the international mobility of the population, even without detailed data on transportation infrastructure. Considering the origin of the virus, it is

probable that commercial trade and social interactions due to workers and professionals of various interrelated companies having globalized, interconnected manufacturing chains, could explain the initial conditions of COVID-19 diffusion in Italy.

If we compare Fig. 3a and b and Fig. 4a and b, it is interesting to note that the magnitude of the interpolation line changes over time, whereas its trend persists. This is an interesting finding, which would require further inquiry. Given that diffusion is probably caused by nonlinear, cumulative interaction, it is probable that initial conditions (i.e., infection rates) have determined a path dependent pattern, which is typical of complex adaptive systems (Moran and Lopez, 2016; Raimbault et al., 2019). Given that previous research COVID-19 infection probably circulated in Europe for several weeks before the first recognized outbreak (Cereda et al., 2020), it is likely that lockdown and social distancing measures have impeded the infection to spread everywhere so that the initial rates have unfolded their effect locally.

In conclusion, a pandemic is a complex phenomenon, involving several aspects, many parameters, and suitable boundary conditions, and it probably cannot be described by simple two-variable correlations. Obviously, certain parameters possibly related to initial contagion (such as GDP, shown in Fig. S1 or commercial trade) show stronger correlations in comparison to other less influential variables or variables that are probably more important to understand subsequent diffusion mechanisms, such as restrictions of social mobility, population density, individual protection measures, transmission rates, hygiene procedures, virus incubation time, meteorological factors, pollution,

etc. We suggest that while initial conditions can be captured by pre-existing economic and environmental factors, the unfolding of contagion is more non-linear and depends on measures, health care system's efficiency and other factors, which could even explain different trajectories (e.g., the different mortality rates in Veneto vs Lombardy, two near regions in Northern Italy with the first virus sites).

This pandemic testifies to the need for a full-comprehensive inter and trans-disciplinary approach, involving different experts, not only from medical and natural sciences, but also from engineering, political, economic, social, and demographic disciplines. This synthesis has been often advocated in 'normal' times. COVID-19 can be the real accelerator of a research paradigms transition towards a synthetic, trans-disciplinary science. Such an effort could also prepare us to respond to other systemic shocks (e.g., climate change) that will require a co-ordinated, rapid capacity of response.

Authors contribution

All the authors contributed to the paper presented methodology and conceptualization. They all contributed to data analysis and paper writing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2020.109814.

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