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International trade as critical parameter of COVID-19 spread that outclasses demographic, economic, environmental, and pollution factors

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ABSTRACT

The novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) that caused the Coronavirus Disease 2019 (COVID-19), generating high numbers of COVID-19 related infected individuals and deaths, is still circulating in 2021 with new variants of the coronavirus, such that the state of emergency remains in manifold countries. Currently, there is still a lack of a full understanding of the factors determining the COVID-19 diffusion that clarify the causes of the variability of infections across different provinces and regions within countries. The main goal of this study is to explain new and main determinants underlying the diffusion of COVID-19 in society. This study focuses on international trade because this factor, in a globalized world, can synthetize different drivers of virus spread, such as mobility patterns, economic potentialities, and social interactions of an investigated areas. A case study research is performed on 107 provinces of Italy, one of the first countries to experience a rapid increase in confirmed cases and deaths. Statistical analyses from March 2020 to February 2021 suggest that total import and export of provinces has a high association with confirmed cases over time (average $r > 0.78$, p-value $<.001$). Overall, then, this study suggests total import and export as complex indicator of COVID-19 transmission dynamics that outclasses other common parameters used to justify the COVID-19 spread, given by economic, demographic, environmental, and climate factors. In addition, this study proposes, for the first time, a time-dependent correlation analysis between trade data and COVID-19 infection cases to explain the relation between confirmed cases and social interactions that are a main source of the diffusion of SARS-CoV-2 and subsequent negative impact in society. These novel findings have main theoretical and practical implications directed to include a new parameter in modelling of the diffusion of COVID-19 pandemic to support effective policy responses of crisis management directed to constrain the impact of COVID-19 pandemic and similar infectious diseases in society.

1. Introduction

The novel severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) that causes the Coronavirus Disease 2019 (COVID-19), generating high numbers of COVID-19 related infected individuals and deaths in society, is still circulating in 2021 with mutations of the coronavirus, such that the state of emergency remains in manifold countries worldwide (CDC, 2021). Understanding the determinants that contribute to the diffusion of COVID-19 is critical for different reasons, such as to provide suitable scientific responses to the still controversial mechanisms of the novel coronavirus transmission dynamics, better define and refine epidemiologic modelling of diffusion, and support appropriate policy responses of crisis management to cope with this environmental threat for the health of population and in general for socioeconomic systems (Bontempi et al., 2020; Coccia, 2020, 2021, 2021c).

Several contributions in different disciplines have tried to propose reasonable responses to the question concerning the territorial heterogeneity of COVID-19 diffusion, not only observed at the global level, but also in different regions of the same county (cf., Coccia, 2020a, 2020b; 2020c, 2021d). The majority of studies and models emphasizes the fundamental and prominent role of the direct transmission occurring from human to human, mainly thought respiratory droplets (Bontempi, 2020; Chang et al., 2020; Sahin et al., 2019). In other scientific research, demographic parameters were among the main considered factors that may explain this spatial heterogeneity (Bertuzzo et al., 2020; Diao et al., 2021). In this context, several papers have investigated the role of the

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social interactions, age, and sex for the observed differences of COVID-19 diffusion (cf., Copiello and Grillenzoni, 2020). Some researchers also propose a correlation between family habits and infection rates (Bayer and Moritz, 2020), but other studies show that specific places can have a high risk to be COVID-19 outbreaks, acting as super-spreaders (Chang et al., 2020; Wang et al., 2020; Yang et al., 2021). A research stream focuses on a fundamental role of environmental and climate factors, such as humidity, wind speed and temperature associated with transmission dynamics of COVID-19 and the territorial differences of pandemic diffusion in society (environmental-to-human transmission; cf., Ahmadi et al., 2020; Bashir et al., 2020; Coccia, 2020c, Coccia, 2021; Eslami and Jalili, 2020; Rosario Denes et al., 2020; Şahin, 2020; Srivastava, 2021). In addition, Engelbrecht and Scholes (2021) argue that COVID-19 can have a seasonal dependence and if herd immunity is not established because vaccination has delayed diffusion for high demand that generates problems of production, recurring waves may generate additional health and socioeconomic issues. Some scholars have suggested a third way of COVID-19 diffusion that can be defined as air pollution-to-human transmission mechanism (see for example, Coccia, 2020, 2021a; Copat et al., 2020; Tung et al., 2021; Zhu et al., 2020). However, data about air pollution can be associated with other determinant factors related to human-to-human transmission mechanism, such as density of population, socioeconomic activity, etc. (Anand et al., 2021; Bontempi, 2020). Several studies analyze the diffusion of COVID-19 pandemic at the city (of few cities) or regional scale; few works investigate transmission dynamics at the national level (Bontempi, 2020a). In this research field, a lot of traditional epidemiological models have been recognized to be unable to predict the scale and dynamics of COVID-19 (Roda et al., 2020). This fact was attributed to the novelty of SARS-CoV-2, as well as statistical problems in the model's calibration (Zhao and Chen, 2020). Other reasons can be due to the limitation of traditional modelling approaches because of the difficulties in the selection of specific and suitable predictors of the pandemic in a non-experimental environment (Ramos et al., 2021). Jones and Strigul (2021) have recently concluded that the COVID-19 pandemic shows a chaotic behavior, with the consequence that the epidemic scale and behavior may be essentially unpredictable. Although models can provide imperfect simulations of the reality, limited by the incapacity to consider all factors determining COVID-19 transmission dynamics in different settings, they will continue to play a fundamental role in guiding public policies through this and future pandemics (Meehan et al., 2020).

In this context, scholars endeavor to propose additional variables that should be considered in these models and may be still not currently evident. In fact, while many factors may be possibly associated with the spread of COVID-19, an investigation is necessary to propose new robust and simple indicators able to embody the role of social interactions associate with people mobility and also economic activities of geographical area. For example, data related to the globalization may contain information concerning human mobility and can provide interesting information about the transmission of infectious diseases (cf., Bontempi et al., 2021; Guan et al., 2020). In particular, globalization has surely contributed to the disease diffusion in high income countries, where the economy and social interactions are more complex within and between countries (Xie et al., 2020). Historical data analysis shows that epidemics can have an accelerated diffusion during economic booms, probably because of the increase of people traveling, with consequent rising of interpersonal contacts (Adda, 2016). Indeed, several economic determinants (e.g., GDP per capita, employment rates, etc.) have been used in previous works to investigate the potential economic factors associated with COVID-19 diffusion (Copiello and Grillenzoni, 2020). In particular, some scholars propose possible correlations between virus diffusion and economical export data, such Oster (2012) that observed a positive relationship between HIV cases and exports in Sub-Saharan Africa. This result was attributed to the increased movement of people, associate with the growth of exports. Some works confirm that richer and more productive areas can have higher levels of infection rates, if compared to provinces with high unemployment rates and rural areas (Diop et al., 2020). These first works suggest that the link between the COVID-19 spread and economic activities should be addressed and studied in depth, evaluating a bi-directional relation of causality. Moreover, it is also plausible that trading requires an increase in human interaction with external people, and that more productive locations are often also more interconnected in economic systems; as a consequence, in the presence of a pandemic, dynamic areas are more likely to be subjected to virus diffusion because of their important economic (and derived social) networks (Bloise and Tancioni, 2021). In fact, it was proposed that economic factors may be considered a reflection of social interactions occurring as a consequence of people mobility (Bontempi, 2020; Bontempi et al., 2020). Current literature concerning economic connection with COVID-19 also shows the negative effects that pandemic and containment policies produced on the economic growth (Coccia, 2021b). Obviously, demographical, environmental, pollution, and meteorological variables should be also comprehensively considered to systematically highlight the eventual role of all these factors in transmission dynamics of COVID-19 and effects in society (Coccia, 2020).

It was recently shown that an interdisciplinary approach can be suitable to analyze the COVID-19 pandemic (Bontempi et al., 2020). Scholars endeavor to propose a comprehensive and systematic analysis of the influence of different variables on COVID-19 diffusion that can help in explaining the mechanisms of diffusion and offer to decision-makers major instruments to control the spread of COVID-19 by efficient control measures (Bontempi, 2021). High levels of economic development can facilitate the pandemic spread, because of advanced transport systems, large cities with high density population, national and international travels for business and vacation, and more group activities (Aycock and Chen, 2021). In this context, the goal of this study is to demonstrate that it is possible to select a new parameter associated with transmission dynamics of COVID-19 that can be considered a suitable indicator to model the human-to-human interactions, englobing local economic, social, and mobility factors. This study proposes that the sum of import and export trade international data can be a complex but suitable indicator of underlying socioeconomic dynamics of geo-economic areas. It allows to consider not only the degree of all potential international relationships, economic dynamics, but also the potential of local and national economies, the wealth of regions and well-being of their population. The time-depended variability of the proposed indicator may be associated to the change of the socioeconomic interaction typologies of COVID-19 diffusion mechanisms.

2. Materials and methods

2.1. Research setting and sample

The paper here is based on a case study of Italy that was the first large European country to experience a rapid increase in COVID-19 related confirmed cases and deaths from February 2020. Italy is located at 43° N latitude and 12° E longitude and has dry summers and mild, wet winters (Mediterranean or dry summer climate). In particular, this study focuses on evolution of the first and second wave of COVID-19 pandemic from March 2020 to February 2021 in Italy, considering 107 provinces of Italy that are the backbone administrative entities of the Italian Republic. Provinces are an administrative division of intermediate level between a municipality and a region. Current 107 institutional bodies of second level in Italy include 80 ordinary provinces, 2 autonomous provinces, 4 regional decentralization entities, 6 free municipal consortia, and 14 metropolitan cities, as well as the Aosta Valley region (which also exercises the powers of a province).

2.2. Sources

Data of COVID-19 infection cases, economic and environmental selected indicators observed at the provincial level for all Italy (107 provinces) were downloaded from different official sources.

In particular, data about the number of COVID-19 cumulative infection cases, from March 2020 to February 2021, were provided by the Italian Civil Protection Department and considered on a daily basis (Protezione civile, 2021).

Data about international trade import and export, and data about the population in the 2019 year are from ISTAT (2021). Also, data about provincial Gross Domestic Product (GDP) in 2017 (the last available year) were downloaded from ISTAT (2021). In particular, the GDP economic indicator includes data deriving from all productive sectors from agricultural, industry, building, trade, to financial sectors.

Data about mean temperatures (Celsius, °C) and mean precipitation value (millimeter, mm), for all cities under study, were downloaded from ISTAT (2021). Temperature indicates the arithmetic over 2007–2016 period.

Data about PM_{10} and $PM_{2.5}$ mean annual concentration, for all cities, were downloaded by ISPRA (2021). They refer to 2018, which is the last available year. Some researches propose association between high levels of these pollutants and confirmed cases of COVID-19 (Coccia, 2020, 2020a, 2020c, 2020a). This study does not consider nitrogen dioxide (NO_2) because of anomalies and ambiguous relations with urban areas having high levels of COVID-19 and well as for missing data for all cities of the province to provide reliable and robust variable for statistical analyses (Savtchenko and Khayat, 2021; Zoran et al., 2020).

2.3. Measures

- *Total Import and export*, total value in Euros (€) in the year 2019, is a complex indicator including manifold factors given by density of population, economic dynamism and people mobility (see Fig. 1).

In fact, to account the SARS-CoV-2 spread differences that can be found in different geographical areas of the same country, a suitable measure must be indicative of human-to-human interactions, resulting the basic recognized mechanism of initial virus diffusion, but it must be also correlated with the people mobility associated with high humans' socioeconomic interactions (Ferretti et al., 2020). Notably, commercial relationships, related to the globalization of companies' value chains and markets, are based on persistent mobility patterns across different countries, and differently from travel for vacation, almost always need close social interaction among individuals (Bontempi et al., 2020). Then, they can be considered the synthetic expression of socioeconomic relationships that are created by economic activities, requiring human contacts associated with business collaboration. In fact, globalization has been accompanied by growing share of international trade. The high level of imports of the resources is indicative of increasing living standards (Rodrigue, 2020). In particular, the economic value of both import and export international trade (in money) of different regions in a country is a main indicator of their living standard of people, economic activities and level globalization (cf., Oster, 2012). Hence, the indicator of the sum of total amount of import and export international trade can be accounted considering the last reported available data (2019 year) for each province in Italy. Fig. 1 represents schematically the determinants that can be included in the new proposed parameter.

- *Confirmed cases of COVID-19* are from March 2020 to February 2021. The study design considers total confirmed cases because it indicates the impact of COVID-19 in society in the presence of a certain level of population and socioeconomic activity (Protezione civile, 2021)

- G*ross Domestic Product* per capita (GDPPC, 2017 period) in provinces is an indicator of wealth of the geographical areas and wellbeing of people. The year 2017 is the last period available, published in 2020 (ISTAT, 2021).

- *Density of population* (km^2 per inhabitants) at December 31, 2019 is a main factor determining human-to human transmission of infectious diseases (Kucharski et al., 2020). This factor can be a proxy of social interaction within and between cities (ISTAT, 2021).

- *Air pollution.* Studies suggest that areas with frequently high levels of air pollution had higher numbers of COVID-19 related infected individuals and deaths (Coccia, 2020, 2020a, 2020a; Martelletti and Martelletti, 2020). This study considers average value of Particulate Matter (PM) 2.5 and 10 in 2018, last year published report (ISPRA, 2021)

- *Atmospheric stability/instability* is measured with days of wind speed greater than 25 knots based on average mean 2008–2018 (SOLE24ORE, 2021). A high wind speed, creating atmospheric instability, seems to reduce the number of infected individuals because it fosters the dispersion of air pollution that can act as carrier of the SARS-CoV-2 in the air, whereas a stable atmosphere with low wind speed prevents the dispersion of air pollutants that remain stagnant in the air with content of bacteria and viruses, such as SARS-CoV-2, generating a higher diffusion of COVID-19 and other infectious diseases (Coccia, 2020a, 2020b, 2021, 2021a, 2020b, 2021a). To put it differently, high concentrations of air pollutants, together with low wind speeds (level of calm/light air in the Beaufort wind scale) may promote a longer permanence of viral particles in the air, thus favoring an indirect means of diffusion of viral infectivity (e.g., SARS-CoV-2), in addition to the direct diffusion with human-to-human transmission dynamics (cf., Coccia, 2021a; Frontera et al., 2020).

- *Average temperatures* in 2007–2016 period (ISTAT, 2021).

- *Rain precipitation* (mm) is based on arithmetic mean in 2007–2016 period (ISTAT, 2021).

It is important to highlight that environmental variable (wind speed, temperature, precipitation) are expected to be not influential on the proposed parameter (international trade data) used to model social interactions. Table 1 reassumes all the data used in this work and their source.

Table 1
Data used in this study and their source.

Data	Period under study	Source (reference)
Total import and export trade value in Euros (€)	2019 period	ISTAT (2021)
Confirmed COVID-19 cases	March 2020–February 2021	Protezione civile, 2021
Gross Domestic Product per capita GDPPC	2017 period	ISTAT (2021)
Density of population km^2 per inhabitants	2019 period	ISTAT (2021)
Particulate Matter (PM) 2.5 and 10	2018 period	ISPRA (2021)
Average days of wind speed greater than 25 knots	2008–2018 period	SOLE24ORE (2021)
Average Temperatures °C	2007–2016 period	ISTAT (2021)
Average Rain precipitation (mm)	2007–2016 period	ISTAT (2021)

2.4. Data analysis procedure

Firstly, variables under study are investigated with descriptive statistics (arithmetic mean, standard deviation, skewness and kurtosis coefficient) to assess the normality of distribution and if it is not normal, a logarithmic transformation is applied to have appropriate variables for parametric analyses.

Secondly, data are analyzed with bivariate correlation by Pearson' s correlation coefficient between two variables given by a specific factor and confirmed cased from March 2020 to February 2021. Correlation has a value in the range [-1, 1]. The sign of the correlation coefficient indicates the direction of the relationship, while the magnitude of the correlation indicates the strength of the relationship:

−1: perfectly negative linear relationship
0: no relationship

Fig. 1. Import-Export as complex factor including manifold drivers of transmission dynamics of COVID-19 in geo-economic areas.

+1: perfectly positive linear relationship

The strength can be as follows:

0.1 < |r | < 0.3 … small/weak correlation
0.3 < |r | < 0.5 … medium/moderate correlation
0.5 < |*r* | … … … large/strong correlation

Test of significance is done considering one-tailed. Moreover, it is applied partial correlation that is a measure of the strength and direction of a linear relationship between two continuous variables whilst controlling for the effect of one or more other continuous variables (also known as 'covariates' or 'control' variables, such as density of population, GDPPC, air pollution, etc.). Test of significance is also done considering one-tailed.

Finally, coefficients of correlation are also visualized in graphs to analyze the temporal aspect of the factors underlying the evolution of COVID-19 pandemic in Italy. Moreover, the relationship of the coefficients of correlation (Import and Export-confirmed cases) on coefficients of correlation (population density - confirmed cases) is analyzed with quadratic model estimated with ordinary least squares to analyze the temporal dynamics and to provide fruitful implications for health and social policies. Statistical analyses are performed with the Statistics Software SPSS® version 26.

3. Results

As many variables, confirmed cases from March 2020 to February 2021 have a not normal distribution because of high levels of skewness and kurtosis coefficient; as a consequence, a logarithmic transformation is applied to have normality in the distribution of variables to provide correct statistical analyses with consistent and robust results.

Firstly, Figs. 2 and 3 report the totally detected COVID-19 infection cases on December 27, 2020 on all the Italian provinces, plotted versus the corresponding population density (Fig. 2a) and international commercial trade data (Import-Export, Fig. 2).

Figs. 2 and 3 seem to show a clear correlation between reported data. However, in-depth statistical data analysis is mandatory to well explain eventual correlations and the main involved variables in relation under study.

Table 2 shows that average coefficient of correlation between Import-Export factor and COVID-19 confirmed cases from March 2020 to February 2021 is higher than $r = 0.78$ (p-value$<.01$), whereas a lower average association with confirmed cases in the same period is with density of population ($r = 0.58$, p-value$<.01$), with GDPPC ($r = 0.64$, p-value$<.01$) and air pollution measured with $PM_{2.5}$ ($r = 0.49$, p-value$<.01$).

Table 3 shows results of partial correlation between Import-Export and COVID-19 confirmed cases, controlling some critical variables. In general, coefficients of correlation are high and confirm the vital role of association with the spread of COVID-19 in society. In particular, from March 2020 to February 2021.

- Controlling population density, average $r' = 0.67$, p-value$<.001$
- Controlling population density and GDPPC, average $r' = 0.44$, p-value$<.001$
- Controlling population density, GDPPC and air pollution, average $r' = 0.40$, from p-value$<.05$ on March-April 2020, p-value .01 over June-September 2020 to p-value .001 over October and subsequent months.
- Finally, controlling climate factors, average $r' = 0.78$, p-value$<.001$

As expected, the use of controlling variables (reported in Table 3) allows to highlight that only environmental parameters (temperature,

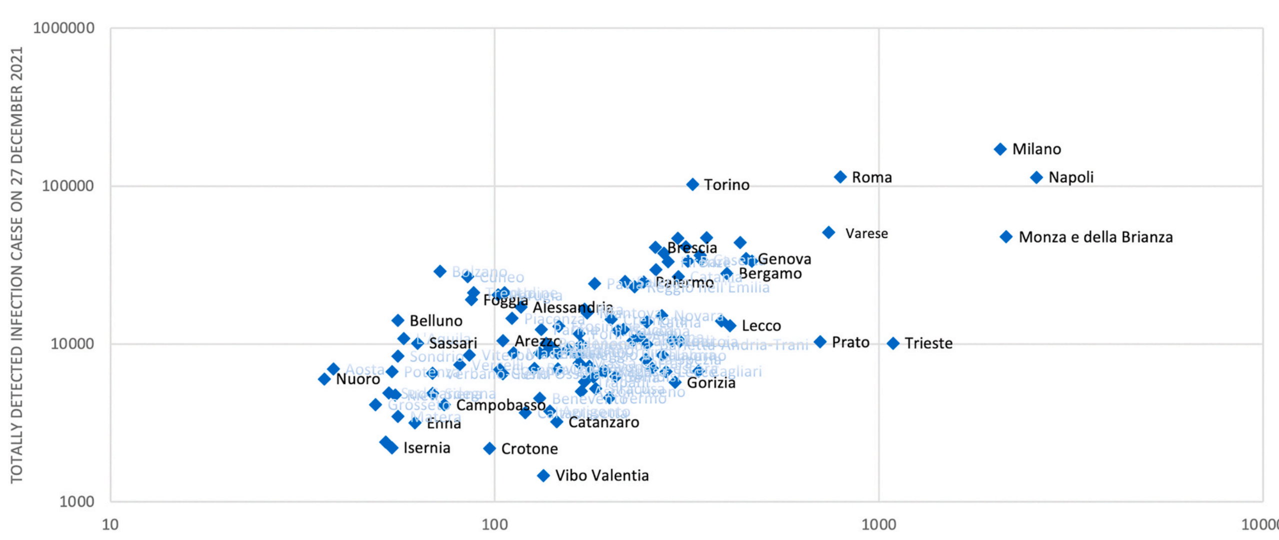

Fig. 2. Totally detected COVID-19 cases in all the Italian provinces (on December 27, 2020) reported versus corresponding 2019 population density (inhabitants/Km^2). All data are plotted in logarithmic scale.

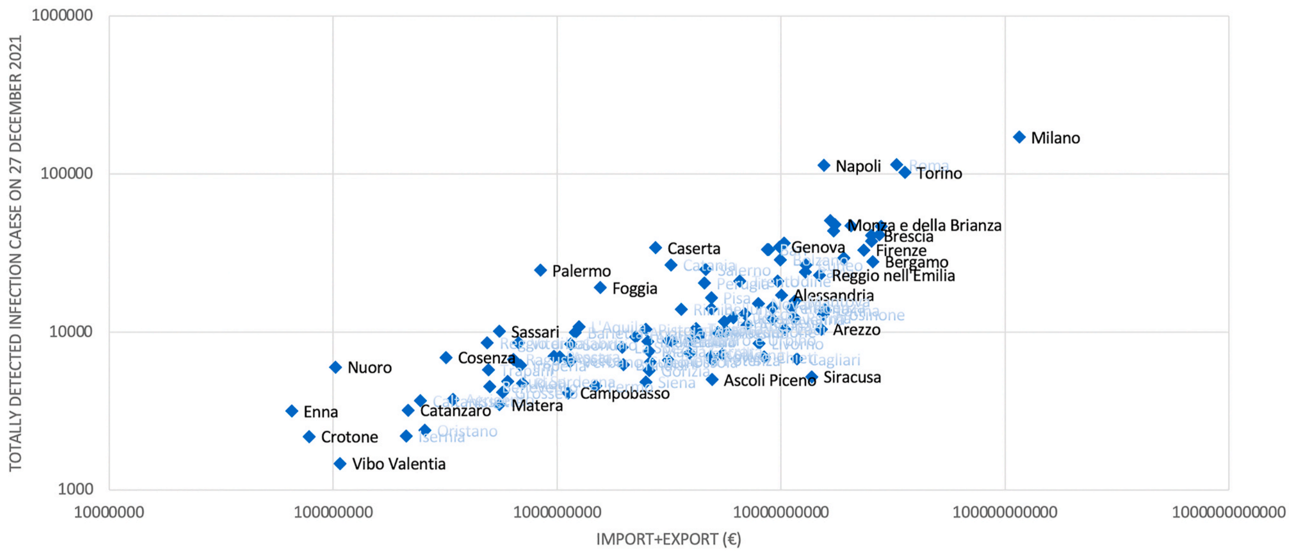

Fig. 3. Totally detected COVID-19 cases in all the Italian provinces (on December 27, 2020) reported versus corresponding 2019 international commercial trade data (€). All data are plotted in logarithmic scale.

Table 2
Bivariate correlation of variables with COVID-19 confirmed cases from March 2020 to February 2021 (log values).

Variables	Import-Export	Density of Population	GDP Manufacturing Sector	GDPPC	Days Wind Speed 25 knots	Air Pollution PM2.5	Air Pollution PM10
Import-Export	1	.573**	.751**	.736**	-.479**	.614**	.568**
Density of Population	.573**	1	.257**	.313**	-0.021	.354**	.471**
GDP Manufacturing Sector	.751**	.257**	1	.848**	-.572**	.618**	.392**
GDP per Capita	.736**	.313**	.848**	1	-.499**	.502**	.309**
Days Wind Speed 25 knots	-.479**	-0.021	-.572**	-.499**	1	-.529**	-.383**
Air Pollution PM2.5	.614**	.354**	.618**	.502**	-.529**	1	.763**
Air Pollution PM10	.568**	.471**	.392**	.309**	-.383**	.763**	1
Cases 15 March 2020	.733**	.487**	.683**	.738**	-.504**	.579**	.553**
Cases 1 April 2020	.765**	.483**	.672**	.739**	-.479**	.570**	.575**
Cases 1 May 2020	.780**	.500**	.675**	.760**	-.495**	.594**	.561**
Cases 1 June 2020	.779**	.504**	.671**	.756**	-.491**	.595**	.560**
Cases 7 July 2020	.779**	.502**	.673**	.759**	-.493**	.593**	.560**
Cases 20 August 2020	.787**	.516**	.662**	.747**	-.489**	.597**	.566**
Cases 20 September 2020	.794**	.545**	.619**	.725**	-.464**	.555**	.568**
Cases 10 October 2020	.800**	.563**	.583**	.697**	-.449**	.514**	.555**
Cases 20 October 2020	.802**	.570**	.550**	.677**	-.451**	.485**	.521**
Cases 30 October 2020	.804**	.596**	.525**	.655**	-.430**	.467**	.497**
Cases 3 November 2020	.805**	.609**	.515**	.646**	-.423**	.460**	.490**
Cases16 November 2020	.800**	.621**	.497**	.620**	-.413**	.442**	.483**
Cases 15 December 2020	.785**	.633**	.461**	.575**	-.402**	.442**	.489**
Cases 27 December 2020	.790**	.636**	.458**	.569**	-.397**	.446**	.498**
Cases 31 December 2020	.789**	.638**	.453**	.565**	-.392**	.444**	.501**
Cases 15 January 2021	.786**	.642**	.433**	.546**	-.374**	.436**	.502**
Cases 24 January 2021	.783**	.642**	.422**	.537**	-.364**	.429**	.498**
Cases 29 January 2021	.782**	.642**	.417**	.533**	-.361**	.426**	.497**
Cases 2 February 2021	.781**	.642**	.414**	.531**	-.359**	.423**	.495**
Cases 4 February 2021	.780**	.642**	.413**	.530**	-.358**	.422**	.494**
Cases 9 February 2021	.780**	.642**	.411**	.529**	-.355**	.419**	.492**

** Correlation is significant at the 0.01 level (1-tailed). **Red** color indicates very strong correlation with coefficient higher than 70%; **Orange** color indicates strong correlation with coefficient from 50 to 69%; **Yellow** color indicates medium correlation with coefficient from 20 to 49%; Negative correlation is with white cells.

Table 3
Partial correlation of total import and export with COVID-19 confirmed cases from March 2020 to February 2021, controlling population density, GDPPC, air pollution, and climate factors (log value).

Correlation	Control, Population Density		Control, Population Density & GDPPC		Control, Population Density & GDPPC & Air Pollution ($PM_{2.5}$)		Control, Temperature, Rain (mm) & Wind Speed	
Variable	Import-Export	Sign. (1-tailed)	Import-Export	Sign (1-tailed)	Import-Export	Sign (1-tailed)	Import-Export	Sign (1-tailed)
Cases 15 March 2020	**0.635**	0	**0.260**	0.004	**0.179**	0.043	**0.638**	0
Cases 1 April 2020	**0.677**	0	**0.333**	0	**0.2200**	0.017	**0.653**	0
Cases 1 May 2020	**0.690**	0	**0.343**	0	**0.256**	0.007	**0.671**	0
Cases 1 June 2020	**0.687**	0	**0.341**	0	**0.255**	0.007	**0.671**	0
Cases 7 July 2020	**0.688**	0	**0.339**	0	**0.252**	0.007	**0.670**	0
Cases 20 August 2020	**0.694**	0	**0.365**	0	**0.283**	0.003	**0.687**	0
Cases 20 September 2020	**0.695**	0	**0.386**	0	**0.328**	0.001	**0.707**	0
Cases 10 October 2020	**0.700**	0	**0.424**	0	**0.394**	0	**0.728**	0
Cases 20 October 2020	**0.701**	0	**0.453**	0	**0.436**	0	**0.738**	0
Cases 30 October 2020	**0.700**	0	**0.472**	0	**0.464**	0	**0.745**	0
Cases 3 November 2020	**0.698**	0	**0.478**	0	**0.473**	0	**0.750**	0
Cases16 November 2020	**0.688**	0	**0.487**	0	**0.484**	0	**0.748**	0
Cases 15 December 2020	**0.662**	0	**0.493**	0	**0.466**	0	**0.736**	0
Cases 27 December 2020	**0.668**	0	**0.508**	0	**0.476**	0	**0.743**	0
Cases 31 December 2020	**0.666**	0	**0.511**	0	**0.478**	0	**0.743**	0
Cases 15 January 2021	**0.661**	0	**0.523**	0	**0.490**	0	**0.745**	0
Cases 24 January 2021	**0.656**	0	**0.526**	0	**0.496**	0	**0.744**	0
Cases 29 January 2021	**0.653**	0	**0.526**	0	**0.497**	0	**0.743**	0
Cases 2 February 2021	**0.651**	0	**0.525**	0	**0.498**	0	**0.742**	0
Cases 4 February 2021	**0.651**	0	**0.525**	0	**0.498**	0	**0.742**	0
Cases 9 February 2021	**0.650**	0	**0.526**	0	0.500	0	**0.742**	0
df	103		102		91		90	

Note: **Red** color indicates very strong correlation with coefficient higher than 70%; **Orange** color indicates strong correlation with coefficient from 50 to 69%; **Yellow** color indicates medium correlation with coefficient from 20 to 49%; Low correlation is with white cells.

wind speed, and rain) are not significant factors for new selected parameter of the international trade, strongly supporting the anthropogenic origin of the proposed variable (Import-Export). Some of social interaction determinants can be indeed also described by controlling variables (see Fig. 1).

Table 4 shows partial correlation, controlling population density with other two main possible drivers of the diffusion of COVID-19:

- Correlation between GDPPC and confirmed cases has an average $r' = 0.59$
- Correlation between air pollution $PM_{2.5}$ and confirmed cases has an average $r' = 0.38$

Both these coefficients of correlation have a lower intensity with similar analyses performed with the factor of Import-Export.

Fig. 4 shows trends of coefficients of correlation of critical variables under study over time. It shows that the variable Import-Export has a rather stable trend, whereas population density has an evolutionary trend of growth, likely following the change of containment measures. Finally, GDPPC and air pollution have evolutionary trends that seem similar, declining when lockdown measures were relaxed, suggesting that they may be indicative of correlated origins.

Fig. 5 shows the relationship of the coefficient of correlation Import-Export/confirmed cases on coefficient of correlation population density/confirmed cases. Estimated relationship with a quadratic model ($y = -5.62x^2+6,5x-1.07$, $R^2 = 0.78$) suggests an inverted *U*-shaped curve with the point of max achieved in October 2020.

4. Discussion

As anticipated above, in the introduction section, we consider the sum of import and export trade international data as an alternative indicator to detect not only the degree of all potential international relationship, but also the relevance of provincial economies and the well-being of their population (see Fig. 1). Fig. 4 shows the time-dependency of the correlation factor between the Import-Export/confirmed cases and the correlation factor between other determinants and infection cases. It is possible to notice that a very high correlation is always established between international trade and COVID-19 cumulative infection cases, considering all provinces under study. Provinces with higher trade data have higher confirmed cases of infection, which can be ascribed to the increased social interactions associated with an intensive growth of economic activities. Indeed, high dependence of infection cases from international trade data can be partially justified considering that Import-Export indicator is strictly connected with GDP that indicates an increase in social interactions (interpersonal relations)

Table 4
Partial correlation of GDPPC and air pollution with confirmed cases from March 2020 to February 2021, controlling population density (log value).

Correlation	Control, Population Density		Control, Population Density	
	GDPPC	Significance (1-tailed)	Air Pollution $PM_{2.5}$	Significance (1-tailed)
Cases 15 March 2020	**0.708**	0	**0.502**	0
Cases 1 April 2020	**0.721**	0	**0.495**	0
Cases 1 May 2020	**0.739**	0	**0.520**	0
Cases 1 June 2020	**0.733**	0	**0.520**	0
Cases 7 July 2020	**0.737**	0	**0.519**	0
Cases 20 August 2020	**0.723**	0	**0.521**	0
Cases 20 September 2020	**0.703**	0	**0.466**	0
Cases 10 October 2020	**0.670**	0	**0.412**	0
Cases 20 October 2020	**0.640**	0	**0.374**	0
Cases 30 October 2020	**0.614**	0	**0.347**	0
Cases 3 November 2020	**0.604**	0	**0.334**	0
Cases16 November 2020	**0.572**	0	**0.309**	0.001
Cases 15 December 2020	**0.511**	0	**0.306**	0.001
Cases 27 December 2020	**0.505**	0	**0.311**	0.001
Cases 31 December 2020	**0.499**	0	**0.308**	0.001
Cases 15 January 2021	**0.474**	0	**0.296**	0.002
Cases 24 January 2021	**0.461**	0	**0.287**	0.002
Cases 29 January 2021	**0.456**	0	**0.283**	0.003
Cases 2 February 2021	**0.453**	0	**0.279**	0.003
Cases 4 February 2021	**0.452**	0	**0.277**	0.003
Cases 9 February 2021	**0.450**	0	**0.273**	0.004
df	103		93	

Note: **Red** color indicates very strong correlation with coefficient higher than 70%; **Orange** color indicates strong correlation with coefficient from 50 to 69%; **Yellow** color indicates medium correlation with coefficient from 20 to 49%

as economic activities increase (Qiu et al., 2020). In particular, it is interesting to observe that the trade data are more correlated to absolute data of COVID-19 diffusion in comparison to GDP. Although this correlation is in accord with the results reported by Ascani et al. (2020) showing that province with the largest economies exhibited the larger share of COVID-19 cases, it is possible that higher significance of correlation between international trade data and infection cases provides more comprehensive information, related not only to economic activities but also to the population well-being and international connectivity (mobility), which are deriving from an intensive social interactions and other activities (see Fig. 1; cf., Aycock and Chen, 2021).

Indeed, even if with lower magnitude, Fig. 4 shows that also a correlation between population density and infections is always established, in accord with results found also in other countries (Coşkun et al., 2021; Rocklöv and Sjödin, 2020; Zhang et al., 2020) and data shown in Fig. 3. The high significance of trade correlation with COVID-19 infection cases can be explained considering that geographical concentration of economic activities in Italy can generate some implications in terms of the spatiality of markets with dense business (and consequently human) interactions that are associated with economic clusters having high international connectivity (Krugman, 1991; Jensen and Kletzer, 2006). This aspects may be traduced in an increased possibility to generate clusters of infections (COVID-19 clusters) that produce large numbers of local contagion cases in specific geo-economic areas (Leclerc et al., 2020). The cluster mode of virus transmission can justify why in some cases, contagious may fail to ignite wider outbreaks (Adam et al., 2020): indeed, clusters are more likely to occur in most rich (productive) areas, with large amount of population where accelerating events are expected to occur with higher probability. With this diffusion model, it is considered that a small proportion of people is responsible for a large proportion of infections (Endo, 2020; Yang et al., 2021).

Fig. 4 also allows to conclude that Import-Export can be considered the main parameter able to model the human-to-human transmission way, that can take into account social interactions associated with well-being and population mobility; then it may be considered a new interesting indicator able to avoid the necessity to select a lot of different parameters (like for example GDP, firm characteristics, value-added per employee, density of livestock units, percentage of employment in agriculture, families size, poverty rate, and so on) with the risk to increase the data fragmentations, uncertainty and analysis complexity.

The transmission dynamics of COVID-19 changed during the course of the epidemic because of the introduction of non-pharmaceutical restriction measures (Bontempi, 2021; Coccia, 2021b). This can be followed by analyzing the evolution of the evaluated correlations factors, during Italy pandemic second wave, and, in particular, at the occurrence of containment measures started on November 3, 2020. Fig. 4 shows the mutual evolution of the selected correlation factors variability, and, in particular, the Import-Export/confirmed cases and population density/confirmed cases. The limitations to peoples' mobility (and the connected activities that can be related to the population well-being) and the suspension of almost all commercial activities (as a consequence of the restriction measures started from November 3, 2020) seem to be reflected in the decrease of Import-Export/confirmed cases correlation coefficient. On the contrary, the correspondent increase of correlation factor related to the population density highlights the increased role of the most proximal personal interactions. Indeed, as reported by Lee (2021), this aspect can be explained considering that the implementation of social distancing measures (closure of restaurants, bars, gyms, cafeterias and so on), allows to reduce the social interactions related to the well-being, with the rate of transmission being more dependent of

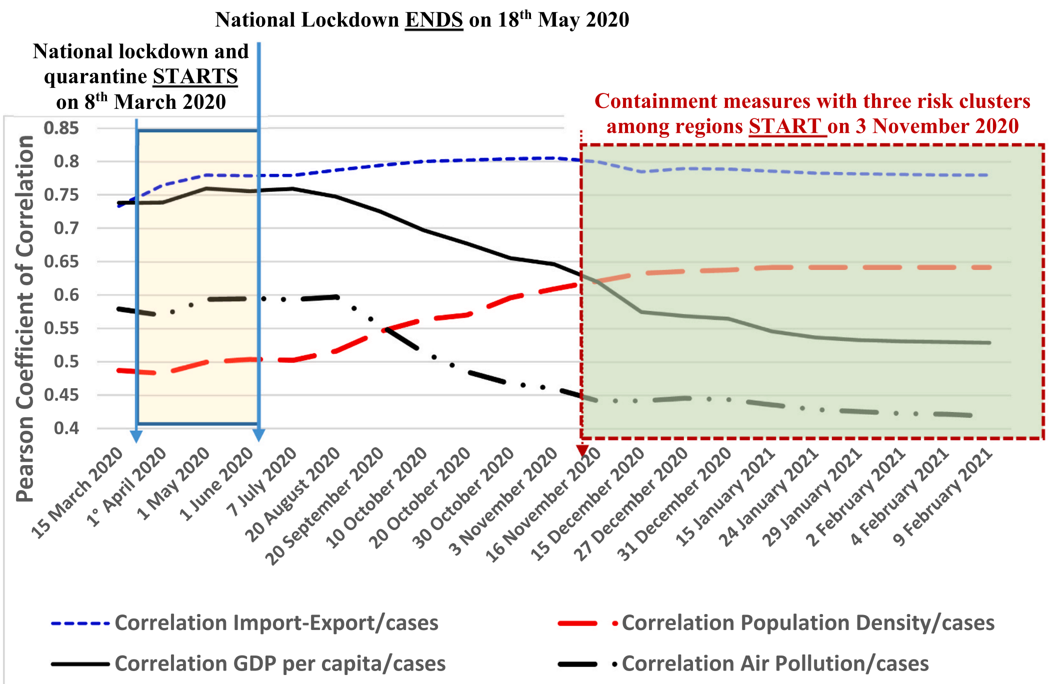

Fig. 4. Trend of coefficients of correlation of critical variable with COVID-19 confirmed cases over time. *Note*: Square with continuous line and highlighted with light yellow color indicates the period of national lockdown in Italy. Square with dotted line and highlighted with green color indicates the period of on-going containment measures with three cluster areas of regions. Measures to control the spread of the COVID-19 within the community are being pursued to safeguard societies and economies, until vaccines and therapies become available and widespread distributed. For first wave was applied a full lockdown, whereas for second wave of COVID-19 pandemic was applied, at regional level, three risk clusters: yellow regions – moderate risk, orange regions – medium-high risk and red regions - high risk (COVID-19 Health system response monitor, 2021). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

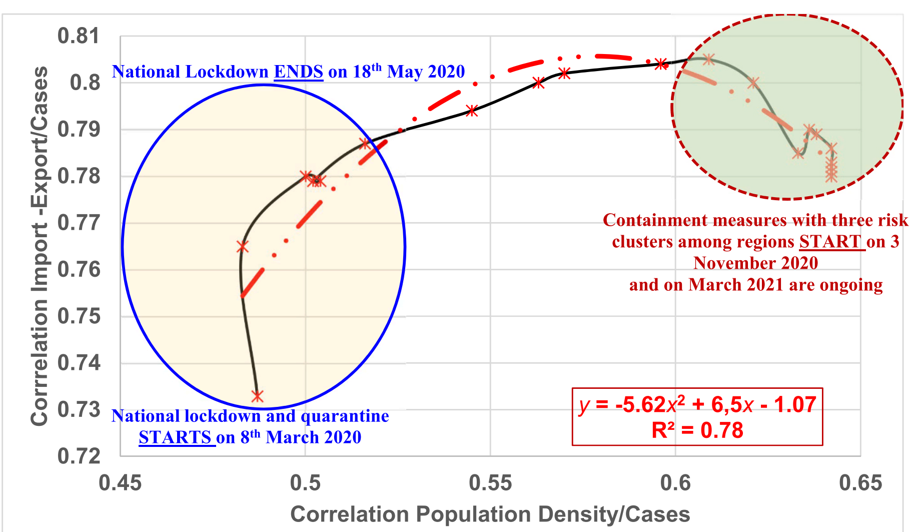

Fig. 5. Relationship of the coefficient of correlation (Import-Export/confirmed cases) on coefficient of correlation (population density/confirmed cases). *Note*: circle with continuous line and highlighted with light yellow color indicates the period of national lockdown in Italy. Circle with dotted line and highlighted with green color indicates the period of on-going containment measures with three cluster areas of regions. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

contagious occurring in local environments (such as families), and as a consequence more connected with population density.

The other correlations that result established between different variables and the COVID-19 infection cases (Table 2), even if statistically relevant may be due to other confounding factors that should be considered in a comprehensive model (Bloise and Tancioni, 2021). In particular, it is important to remember that, except for weather conditions (see Table 3), some concurrent factors (as for example GDP and air pollution) are anthropic in nature, thus, they are expected to be connected to humans' activities (for example, Fig. 4 shows that GDPPC and air pollution correlations follow the same temporal behavior, with the possibility that PM can represent an indicator of GDP). Moreover, as the use of few explanatory variables minimizes the risk of overfitting (Bloise and Tancioni, 2021), and the use of the international trade variable allows to obtain a high correlation, we obtained a good description of the mechanism of diffusion of COVID- 19 by focusing on two variables: Import-Export and population density (see Figs. 4 and 5). This newly analysis about COVID-19 diffusion in all provinces of Italy strongly suggests that infections can be minimized by strict initial lockdowns policies, involving also economic activities, with the possible

Table 5
International trade factor as critical parameter of the spread of COVID 19 that outclasses economic, demographic, and environmental pollution factors.

Average Bivariate Correlation from March 2020 to February 2021	*r*	Significance (1-tailed) *p*-value
Import - export factor and confirmed cases	**0.78**	**0.01**
GDPPC and confirmed cases	0.64	0.01
Density of population and confirmed cases	0.58	0.01
Air pollution ($PM_{2.5}$) and confirmed cases	0.49	0.01
Average Partial Correlation from March 2020 to February 2021		
Controlling population density		
Import - export factor and confirmed cases	**0.67**	**0.001**
GDPC and confirmed cases	0.59	0.001
Air pollution $PM_{2.5}$ and confirmed cases	0.38	0.001–0.01

consequence to reduce the duration of the measures of containment (cf., Mahato et al., 2020; Liu et al., 2021). This strategy is similar to other actions that also limit economic loss (Qiu et al., 2020). Finally, by applying a time-dependent correlation factors analysis, it is also possible to evaluate some control policies during a pandemic, allowing to understand the main contagious origins. This aspect may also give to decision-makers instruments to set additional control measures, as well as the way to relax restrictions to minimize the loss of acquired benefices with the aim to prevent the failure of the already adopted measures.

5. Concluding observations

This work investigates the geographical diffusion at provincial level of the COVID-19 in Italy, with the aim to identify the main parament that can model the humans' factors causing the local diffusion of the pandemic. This work was motivated by the observation of a heterogeneous spatial diffusion of pandemic in Italian regions. The key hypothesis is that the international trade data can be selected as a strong indicator to explain the diffusion of COVID-19 and spatial variability because it embodies different fundamental parameters that impact the size of infections across different geo-economic areas of provinces (cf., Fig. 1).

On the same time other parameters such as population density, GDP, wind speed, and particulate matter (PM) concentrations, are considered in the evaluations but results show an association with confirmed cases from March 2020 to February 2021 lower than international trade (Table 4).

In fact, Table 5 schematically summarizes how international trade factor is a critical parameter associated with the spread of COVID 19 that outclasses economic, demographic, and environmental pollution factors.

This is justified considering that trade data can be used to account the social interactions in the frame of a human-to-human mechanism of contagion diffusion, following the cluster model of virus spread. Then the proposed parameter results to be suitable to englobe different aspects of human's interactions, also connected with cluster models of pandemic diffusion (Fig. 1). In addition, a similar study, based on 52 regions of three large European countries (i.e. all the regions of France, Italy, and Spain) confirms proposed results here: a strong positive correlation between the international trade data and the ICU (Intensive Care Units) hospitalized patients, suggested a high impact of COVID-19 in society (Bontempi et al., 2021). Considering the significance of international trade parameter, it is possible to infer that other confounding variables (like environmental conditions, such as temperature) may also play a role in the spread of COVID-19 and eventually considered as additional parameters, not included in the international trade (see Table 3).

Overall, then, this study by a time-dependent analysis made during the COVID-19 pandemic in Italy shows that the proposed indicator of virus diffusion allows to exploit the consequence of restriction policies implementation, being the reflection of the change of behavior in humans' interactions. The results here are important because the most suitable pandemic protective behavior depends on scientific understanding of the virus spread mechanisms and how they can evolve over time and space if boundary conditions are modified (for example by introduction of containment and mitigation measures). In fact, understanding this relationship is fundamental to enable decision makers to suitably design and execute non-pharmaceutical actions of public policy.

At the best of authors knowledge this is the first paper showing that international trade data can be considered one of the main indicators of diffusion of COVID-19 spread in all 107 Italian provinces, allowing to follow the contagious dynamics over time. The proposed approach is unique not only for the data that are reported, but also in pooling and comparing information from all Italian provinces at once, providing main general theoretical and practical implications for future studies on COVID-19 pandemic and epidemics similar to COVID-19. However, it is extremely important to highlight that, despite the correlation factors behavior can allow to extract information about contagious mechanisms, they cannot be directly related to the infection magnitude, i.e. to the total amount of existing contagious cases. This aspect means that these results can be used to analyze the transmission dynamic of COVID-19 (also considering more local variability), but they are not predictive of the infections. To conclude, results of this study are of course tentative because based on data before the mutations of the novel coronavirus in Italy. There is need for much more detailed research into the relations between the role of import-export commercial activity, climate, environmental factors and confirmed cases and death of COVID-19 to provide additional findings to support updated strategies of crisis management to cope with future pandemic threat.

Authors contribution

Both authors contributed to the paper presented methodology and conceptualization. Both authors 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. No funding was received for this study.

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