



# Associations between institutional-social-ecological factors and COVID-19 case-fatality: Evidence from 134 countries using multiscale geographically weighted regression (MGWR)

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## ABSTRACT

During the period in which the Omicron coronavirus variant was rapidly spreading, the impact of the institutional-social-ecological dimensions on the case-fatality rate was rarely afforded attention. By adopting the diagnostic social-ecological system (SES) framework, the present paper aims to identify the impact of institutional-social-ecological factors on the case-fatality rate of COVID-19 in 134 countries and regions and test their spatial heterogeneity. Using statistical data from the Our World In Data website, the present study collected the cumulative case-fatality rate from 9 November 2021 to 23 June 2022, along with 11 country-level institutional-social-ecological factors. By comparing the goodness of fit of the multiple linear regression model and the multiscale geographically weighted regression (MGWR) model, the study demonstrated that the effects of SES factors exhibit significant spatial heterogeneity in relation to the case-fatality rate of COVID-19. After substituting the data into the MGWR model, six SES factors were identified with an R square of 0.470 based on the ascending effect size: COVID-19 vaccination policy, age dependency ratio, press freedom, gross domestic product (GDP), COVID-19 testing policy, and population density. The GWR model was used to test and confirm the robustness of the research results. Based on the analysis results, it is suggested that the world needs to meet four conditions to restore normal economic activity in the wake of the COVID-19 pandemic: (i) Countries should increase their COVID-19 vaccination coverage and maximize COVID-19 testing expansion. (ii) Countries should increase public health facilities available to provide COVID-19 treatment and subsidize the medical costs of COVID-19 patients. (iii) Countries should strictly review COVID-19 news reports and actively publicize COVID-19 pandemic prevention knowledge to the public through a range of media. (iv) Countries should adopt an internationalist spirit of cooperation and help each other to navigate the COVID-19 pandemic. The study further tests the applicability of the SES framework to the field of COVID-19 prevention and control based on the existing research, offering novel policy insights to cope with the COVID-19 pandemic that coexists with long-term human production and life for a long time.

## 1. Introduction

At the end of November 2019, the first human case of Coronavirus Disease (COVID-19) was registered in Wuhan, China [1]. Shortly afterwards, the virus began to rapidly spread around the world. The World Health Organization (WHO) was deeply concerned about the rate and scale of the virus's spread and the severity of the disease, leading it to

declare a global pandemic in March 2020 [2].

The Omicron variant of SARS-Cov-2 virus (B.1.1.529) was first detected in South Africa on 9 November 2021; by 26 November 2021, it was regarded as a variant of concern [3]. Since then, the variant has spread worldwide: as of October 2022, the Omicron variant remains the most prevalent strain of the virus globally, leading to a significant increase in COVID-19 cases. Although the virus continues to circulate and

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cause disease, most countries and regions in the world have announced a partial or complete lifting of COVID-19 restrictions to revive shuttered national economies and reinvigorate society. According to statistics published by Travel Off Path [4], as of October 20, 2022, 115 countries have completely lifted travel restrictions or entry requirements. As the world moves into this new phase of adjusting to life with COVID-19, the issue of reducing the adverse impact of COVID-19 on human health in normal life has become a key concern for all countries.

In contrast with previous COVID-19 variants, the Omicron variant causes lower disease severity in infected persons, although its high transmissibility and immunity escape may nevertheless pose a threat to co-morbid patients [3]. It should be emphasized that, following multiple waves of COVID-19 infections, many institutional-social-ecological factors have been changed, including but not limited to improved vaccination rates, changes in population structures, and revised anti-epidemic policies [5,6]. Therefore, in this new public health context, relevant research findings require an urgent update to reduce the negative impact of COVID-19 on health, society and the economy as nations attempt to return back to a normal living environment. At the same time, it is necessary to devise ways to cope with resource shortages, social disorder, economic loss, and other issues stemming from the pandemic, with the ultimate aim of realizing the dynamic elimination of COVID-19 worldwide.

Against the above research background, the objective of the present study is to identify key institutional-social-ecological factors influencing COVID-19 fatality worldwide during the period in which Omicron has been the dominant variant. Drawing on a range of exogenous factors, the study integrates the health and the social-ecological system (SES) framework to comprehensively and systematically identify institutional-social-ecological factors influencing the COVID-19 case-fatality rate at the country level. More precisely, based on three SES primary components, namely resource systems and units, governance systems, and actors, this study identifies which SES attributes and sub attributes are

significant and effective in explaining and thus curbing the case-fatality rate of COVID-19 in the context of pandemic normalization worldwide.

The predecessor of the social-ecological system (SES) framework is the institutional analysis and development (IAD) framework developed by Ostrom [7]. The former is typically used by social scientists to evaluate the effects of institutional arrangements, physical environments, and local communities in explaining a certain contextual outcome [8]. Notably, it is considered to be a comprehensive tool for communication amongst different disciplines that can achieve a better understanding of a given situation. However, the IAD framework has been widely criticized by scholars due to its lack of diversity and the complexity of natural systems and processes [9]. In response to these criticisms, Ostrom then proposed the SES framework [10]. Building on the IAD framework, the SES framework provides a more detailed, variable-oriented analysis of the social-ecological system. Specifically, it redresses the inconvenience of hierarchical analysis experienced with the IAD framework by decomposing the variables layer by layer. As shown in Fig. 1, the SES framework consists of four core systems: two systems representing the external environment and the interaction arena and the outcomes, respectively. McGinnis and Ostrom [11] later developed a range of secondary sub-variables under the systems, which includes more than 50 variables (see Fig. 2). However, although the SES framework is more comprehensive, the complexity of the subcategory variables definition hinders concrete application by users [12]. Therefore, consistent with the application spirit of IAD, we are able to diagnose and explain the interaction and outcomes of a situation using the identified SES attributes [13]. In the present study, the core systems in the SES framework are reorganized into resource systems and units (RSU), governance systems (GS), and actors (A).

The SES framework provides researchers with systematic networks of action situations, including variable-oriented and process-oriented lines of demonstration, thereby allowing scholars to make more informed decisions [9]. It should be pointed out that the SES framework

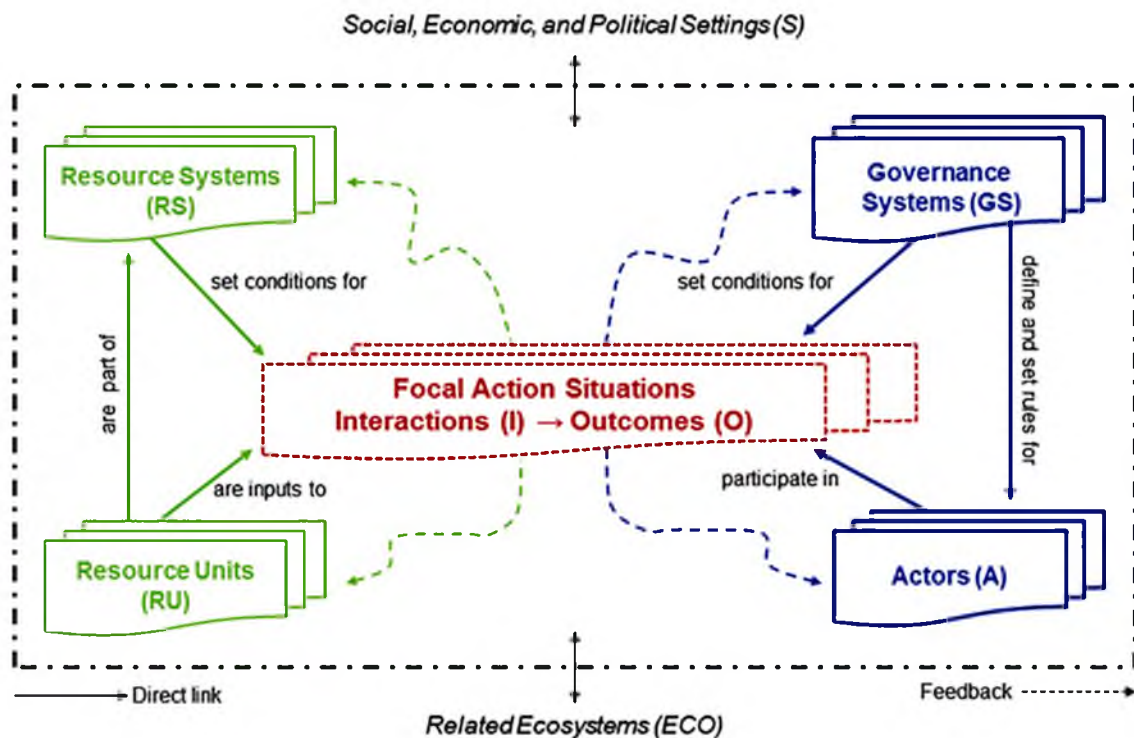


Fig. 1. Social-ecological system (SES) framework. Source: Adapted from McGinnis and Ostrom [11]

First-tier variable	Second-tier variables
Social, economic, and political settings (S)	S1 – Economic development S2 – Demographic trends S3 – Political stability S4 – Other governance systems S5 – Markets S6 – Media organizations S7 – Technology
Resource systems (RS)	RS1 – Sector (e.g., water, forests, pasture, fish) RS2 – Clarity of system boundaries RS3 – Size of resource system RS4 – Human-constructed facilities RS5 – Productivity of system RS6 – Equilibrium properties RS7 – Predictability of system dynamics RS8 – Storage characteristics RS9 – Location
Governance systems (GS)	GS1 – Government organizations GS2 – Nongovernment organizations GS3 – Network structure GS4 – Property-rights systems GS5 – Operational-choice rules GS6 – Collective-choice rules GS7 – Constitutional-choice rules GS8 – Monitoring and sanctioning rules
Resource units (RU)	RU1 – Resource unit mobility RU2 – Growth or replacement rate RU3 – Interaction among resource units RU4 – Economic value RU5 – Number of units RU6 – Distinctive characteristics RU7 – Spatial and temporal distribution
Actors (A)	A1 – Number of relevant actors A2 – Socioeconomic attributes A3 – History or past experiences A4 – Location A5 – Leadership/entrepreneurship A6 – Norms (trust-reciprocity)/social capital A7 – Knowledge of SES/mental models A8 – Importance of resource (dependence) A9 – Technologies available
Action situations: Interactions (I) → Outcomes (O)	I1 – Harvesting I2 – Information sharing I3 – Deliberation processes I4 – Conflicts I5 – Investment activities I6 – Lobbying activities I7 – Self-organizing activities I8 – Networking activities I9 – Monitoring activities I10 – Evaluative activities O1 – Social performance measures (e.g., efficiency, equity, accountability, sustainability) O2 – Ecological performance measures (e.g., overharvested, resilience, biodiversity, sustainability) O3 – Externalities to other SESs
Related ecosystems (ECO)	ECO1 – Climate patterns ECO2 – Pollution patterns ECO3 – Flows into and out of focal SES

Fig. 2. Second-tier variables of a social-ecological system. Source: Adapted from Ostrom [14]

has already been applied in other studies of public health and safety [15]. As early as 2021, Ling et al. [13] used a qualitative content analysis method to study the ability of the institutional-social-ecological factors of seven countries in the Asia-Pacific region to curb the first wave of the COVID-19 pandemic based on the SES framework. To both better conform to the current global public health environment and improve on Ling et al. [13] research, this study employs the SES framework as the

theoretical framework to identify the institutional-social-ecological factors on the case-fatality rate of COVID-19 and test their spatial heterogeneity. To do so, it compares the regression results of the multiple linear regression model and multiscale geographically weighted regression (MGWR) model and identifies the institutional-social-ecological factors that affect the case-fatality rate of COVID-19 in 134 countries and regions during the Omicron variant epidemic period. The

robustness of the study is then tested using a geographically weighted regression (GWR) model.

The following sections of the paper further elaborate on the topic in terms of (i) materials and conceptual framework; (ii) research methods; (iii) results; (iv) discussions; and (v) conclusions and recommendations.

## 2. Materials and conceptual framework

A total of 11 attributes (with four ecological attributes, four institutional attributes, and three social attributes) were outlined to analyze the institutional-social-ecological factors affecting the case-fatality rate of COVID-19 during the Omicron variant epidemic period. The 11 factors were derived from mainstream relevant literature and research findings related to COVID-19 in terms of potential factors that affect the case-fatality rate. These variables are defined and described below.

### 2.1. Outcomes (O)

According to the research objective, the dependent variable of the study is the reported case-fatality rate of COVID-19. Fatality rate is defined as the number of individuals who died of COVID-19 divided by the number of confirmed cases over a certain period of time [16].

Resource units and systems (RSU):

“Liberal democracy” is a variable used to measure the democratic level of a country. Generally speaking, when a country or region elects its government through regular, free, and fair elections, it is said to be democratic. Democratic countries have a greater incentive than autocratic countries to provide welfare, health-related resources, and services to most citizens as the government can be voted out [17]. However, some studies have shown that although the life expectancy of the population in democratic countries is longer, such countries are less able to control infectious diseases (see [18,19]). The reason for this could be that the level of democracy may be related to the government's ability to implement mandatory public health measures during the pandemic (Economist Intelligence [20,21,22]). In this study, “liberal democracy” was measured by the Varieties of Democracy (V-Dem) experts' evaluation index, which combines information on voting rights, the freedom and fairness of elections, freedoms of association and expression, civil liberties, and executive constraints. It ranges from 0 (least democratic) to 1 (most democratic).

“Gross domestic product (GDP)” is a monetary measure of the market value of all the final goods and services produced and sold (not resold) by a country within a defined time period. At present, few studies have been conducted investigating the severity and case-fatality rate of COVID-19 in terms of GDP. Hasan et al. [23] observed a positive correlation between GDP and COVID-19 case-fatality rate in both the pre- and post-peak periods of the COVID-19 epidemic. However, due to the long-term nature of the COVID-19 pandemic, after several waves of the epidemic, those countries and regions with higher GDPs may have more disposable funds to dedicate to public health and curbing the spread of the pandemic, whereas those countries and regions with low GDPs may be eager to restore production by reducing the policy strength of pandemic control.

“Nurses per 1000 people” is the variable used to measure the medical service available. Most of the past studies on the COVID-19 pandemic measured the level of medical services using the number of hospital beds [24,25,22]. However, the number of hospital beds may be a monolithic measure of medical resources, as multiple studies have proven that the severity of symptoms of a patient infected with the Omicron variant has decreased [26,27,28,29]. Therefore, the proportion of COVID-19-infected individuals who need to be hospitalized during the epidemic of the Omicron variant has decreased significantly compared to other waves. Additionally, infected individuals need more early treatment and basic care, as well as timely detection in the initial stage of COVID-19 infection. On this basis, the present study instead used the “nurses per 1000 people” to measure the medical level of a country or region.

The media is an important factor affecting the implementation of pandemic prevention measures. Fake news can increase susceptibility to misinformation and distrust of the government amongst the public, which will reduce the implementation of the government's pandemic restriction policies, such as by encouraging vaccination hesitancy [30,31]. Limiting the spread of infectious diseases largely depends on citizens' attitudes, behaviors, and reaction and action abilities [21,32,33]. This factor was measured by the Reporters Sans Frontières' World Press Freedom Index which evaluates the freedom of journalists to publish news, ranging from 0 (total freedom) to 100 (no freedom).

### 2.2. Governance system (GS)

Higher testing rates can reduce the severity and mortality of COVID-19 [34]. In their study, Hasan et al. [23] demonstrated that prior to the peak mortality period, an increase of 1000 COVID-19 tests decreased the case-fatality rate by 2%. Elsewhere, Di Bari et al. [35] proved that expanded COVID-19 testing policies (i.e., that promote testing) can effectively curb the threat of the COVID-19 pandemic. In the present study, the COVID-19 testing policy is used to measure the popularity of COVID-19 testing in a country or region. The COVID-19 testing policy was measured through four levels: (1) No testing policy; (2) Only those who both (a) have symptoms and also (b) meet specific criteria; (3) Testing of anyone showing COVID-19 symptoms; (4) Open public testing.

Although COVID-19 contact tracing has been incorporated into many studies investigating the transmission of COVID-19 [36,37], few studies have analyzed the impact of COVID-19 contact tracing on COVID-19 case-fatality rates. It is suggested that COVID-19 contact tracing can detect infected individuals in the early stage of infection, thus allowing them to be treated before severe illness develops or fatality occurs. Therefore, in this study, the impact of the COVID-19 contact tracing policy on the case-fatality rate was studied. COVID-19 contact tracing policy was measured by three levels: (1) No tracing; (2) Limited tracing; (3) Comprehensive tracing.

During the COVID-19 pandemic, the production and life of all countries and regions are affected. Low-income individuals with insecure basic living conditions will still go out to work in order to meet their basic living needs during the COVID-19 pandemic. It should also be noted that low-income people may not be able to afford the cost of treatment following COVID-19 infection. It is therefore to be expected that most studies have shown that the COVID-19 infection rate and case-fatality rate of low-income people are high [38,39,40,41]. In response to this issue, some countries implemented economic support measures to reduce people's economic pressures during the pandemic and control the transmission of COVID-19, including income support and debt or contract relief. According to Oxford COVID-19 Government Response Tracker [42], income support policy can be measured by three levels: (1) No income support; (2) Government replaces less than 50% of lost sales; (3) Government replaces 50% or more of lost sales. Additionally, debt or contract relief was also measured by three levels: (1) No debt relief; (2) Narrow relief, specific to one kind of contract; (3) broad debt/contract relief. In the study, the mean value of these two variables was calculated to combine them into a single variable: economic support policy.

Vaccines can effectively reduce the case-fatality rate of COVID-19 [43]. Countries have adopted various vaccine delivery policies in an effort to improve vaccination rates amongst the population and minimize the harm from COVID-19. According to the promotion of vaccines, the COVID-19 vaccination policy was measured by three levels: (1) No availability; (2) Available to key workers, the clinically vulnerable, the elderly, and some others; (3) Universal availability. Since the COVID-19 restriction policies on day-to-day activities are different across countries and regions, the study calculated the average value of the sub-variables under the government systems as the research value.

2.3. Actors (A)

A large number of studies have proved that population density affects COVID-19 infection and mortality rates [44,45,46]. However, few studies have demonstrated the impact of population density on the case-fatality rate of COVID-19. Hasan et al. [23] identified a significant positive correlation between population density and COVID-19 case-fatality rate, although the study did not put forward any explanation for this relationship. With this in mind, the present study demonstrated the impact of population density on the case-fatality rate of COVID-19, which was measured by the number of people per km<sup>2</sup> of land area.

Many studies have observed a significant positive correlation between population age and the COVID-19 case fatality rate

[23,47,24,48,22]. However, Fan et al. [6] highlighted that the age structure of infected population will have changed following multiple waves of the pandemic. Hasan et al. [23] showed that the infection rate of young people was rising globally, with people under 40 years old in the United States, Israel and Portugal accounting for the majority of new cases. The study studied the effect of age on the COVID-19 case fatality rate through the age dependency ratio, which is the sum of the young population (under age 15) and elderly population (age 65 and over) relative to the working-age population (ages 15 to 64). As the susceptible population of COVID-19 in the Omicron variant epidemic period is more likely to be the labor group, the increased level of social contact will facilitate the virus's spread [49], such that case-fatalities may be concentrated in those groups that frequently engage in social activities.

**Table 1**  
Definitions of variables.

SES systems	Variables	Measurement level	Variables' assignment	Hypothesis
Outcomes (O)	COVID-19 case-fatality rate	Interval-ratio level of measurement	Case-fatality rate of COVID-19 in various countries/regions	
Resource systems and units (RSU)	Liberal democracy	Interval-ratio level of measurement	Based on the expert assessments and index by V-Dem. It combines information on voting rights, the freedom and fairness of elections, freedoms of association and expression, civil liberties, and executive constraints. It ranges from 0 to 1 (most democratic).	H1: Liberal democracy has a negative impact on the case-fatality rate of COVID-19.
	Gross domestic product (GDP) Nurses per 1000 people	Interval-ratio level of measurement Interval-ratio level of measurement	National gross domestic product adjusted for inflation and for differences in the cost of living between countries. Number of nurses per 1000 people. Nurses include professional nurses, professional midwives, auxiliary nurses, auxiliary midwives, enrolled nurses, enrolled midwives and other associated personnel, such as dental nurses and primary care nurses.	H2: Countries with higher GDP have lower case-fatality of COVID-19. H3: Number of nurses per 1000 people has a positive impact on the case-fatality rate of COVID-19.
Governance systems (GS)	Press freedom	Interval-ratio level of measurement	Reporters sans Frontières' World Press Freedom Index combines expert assessments with data on violence against journalists. It ranges from 0 to 100 (no freedom).	H4: Press freedom has negative impact on the case-fatality rate of COVID-19.
	COVID-19 testing policy	Interval-ratio level of measurement	No testing policy = 1; Only those who both (a) have symptoms and also (b) meet specific criteria (e.g. key workers, admitted to hospital, came into contact with a known case, returned from overseas) = 2; Testing of anyone showing COVID-19 symptoms = 3; Open public testing (e.g. "drive through" testing available to asymptomatic people) = 4 Due to different daily policies, the variable value is the mean value during 9 November 2021 to 23 June 2022.	H5: More extensive COVID-19 testing policy has positive impact on the case-fatality rate of COVID-19.
	COVID-19 contact tracing policy	Interval-ratio level of measurement	No tracing = 1; Limited tracing (only some cases) = 2; Comprehensive tracing (all cases) = 3 Due to different daily policies, the variable value is the mean value during 9 November 2021 to 23 June 2022.	H6: COVID-19 contact tracing policy has positive impact on the case-fatality rate of COVID-19.
	Economic support policy	Interval-ratio level of measurement	This variable is a combination of "Income support" and "Debt or contract relief". "Income support" is measured by three-levels: No income support = 1; Government is replacing less than 50% of lost salary (or if a flat sum, it is less than 50% median salary) = 2; Government is replacing 50% or more of lost salary (or if a flat sum, it is greater than 50% median salary) = 3 "Debt or contract relief" is also measured by three levels: No debt relief = 1; Narrow relief, specific to one kind of contract = 2; Broad debt/contract relief = 3 The value of "economic support" is the mean value of the two variables. Due to different daily policies, the variable value is the mean value during 9 November 2021 to 23 June 2022.	H7: Economic support policy has positive impact on the case-fatality rate of COVID-19.
Actors (A)	COVID-19 vaccination policy	Interval-ratio level of measurement	No availability = 1. Availability key workers, the clinically vulnerable, the elderly and some others = 2, Universal availability = 3 Due to different daily policies, the variable value is the mean value during 9 November 2021 to 23 June 2022.	H8: COVID-19 vaccination policy has positive impact on the case-fatality rate of COVID-19.
	Population density	Interval-ratio level of measurement	The number of people per km <sup>2</sup> of land area	H9: Higher population density has negative impact on the case-fatality rate of COVID-19.
	Age dependency ratio	Interval-ratio level of measurement	The age dependency ratio is the sum of the young population (under age 15) and elderly population (age 65 and over) relative to the working-age population (ages 15 to 64).	H10: Age dependency ratio has negative impact on the case-fatality rate of COVID-19.
	Share of the population using the internet	Interval-ratio level of measurement	Number of people using Internet per 100 people.	H11: Share of the population using the internet has positive impact on the case-fatality rate.

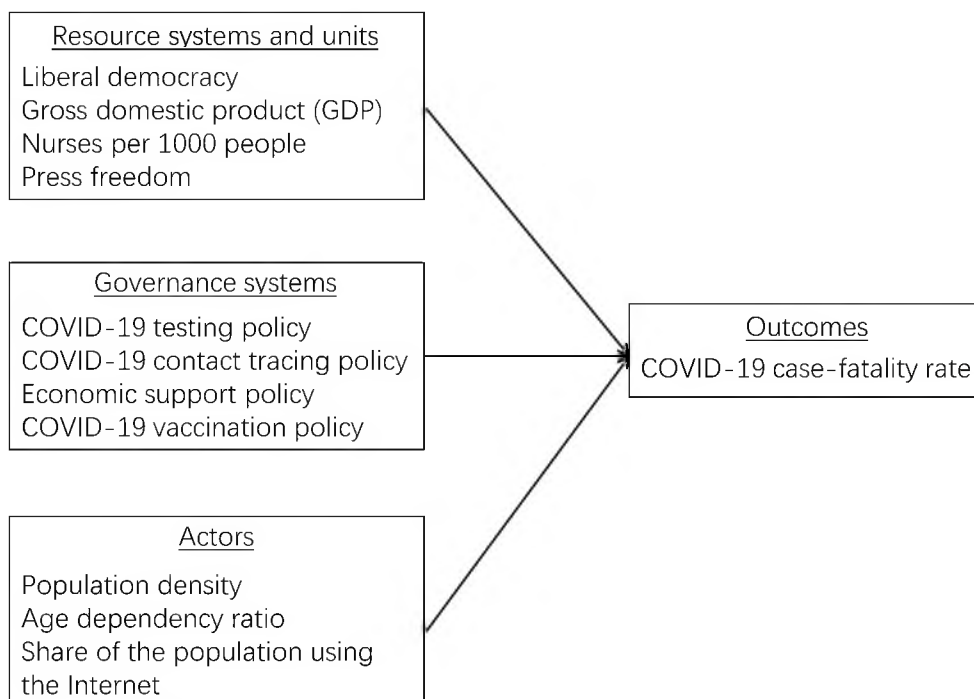


Fig. 3. Conceptual framework.

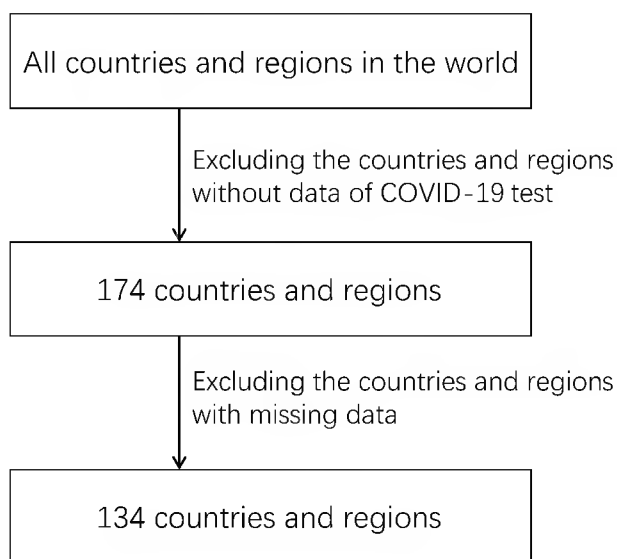


Fig. 4. Process of stratified purposive sampling.

During the pandemic period, some countries used the Internet to work at home and study to avoid the spread of the COVID-19 virus, so that those with low immunity could avoid death caused by COVID-19 infection. However, due to the Internet, misinformation on news media and social media is likely to hinder the promotion of public health policies, such as COVID-19 vaccination [50]. In the study, we analyzed the impact of the proportion of the population using the Internet on the COVID-19 case-fatality rate in each country or region; “share of the population using the Internet” was measured by the number of people using the Internet per 100 people in each country or region.

According to the literature review, the following research hypotheses are proposed. The details of each variable and research hypotheses are shown in Table 1.

Based on the Ostrom's SES framework and research variables, the conceptual framework of the study is shown in Fig. 3.

### 3. Research methods

#### 3.1. Study area

This study adopted countries and regions around the world as the study area. To minimize any errors and limit bias in the study, stratified purposive sampling was used to put together a sample of countries and regions, which together form the research object. First, the study sampled those countries and regions with COVID-19 testing data from 9 November 2021 to 23 June 2022. It should be pointed out that the uncertainty of COVID-19 testing statistics can affect the accuracy of the COVID-19 case-fatality rate. In this step, 174 countries and regions were sampled, after which, those countries and regions with missing data were excluded from the sample according to the research variables. Ultimately, 134 countries and regions remained in the research sample. The process of stratified purposive sampling is shown in Fig. 4.

#### 3.2. Data collection

The data necessary for the empirical estimation of 11 institutional-ecological variables on the COVID-19 case fatality rate were collected according to the conceptual framework development (see Fig. 3). According to Mathieu et al. [51], after 23 June 2022, the reporting methods and standards used by countries have diverged, with some countries now reporting data less frequently. On this basis, the data after 23 June 2022 are not referential. Therefore, the time range of data is from 9 November 2021 to 23 June 2022. The data of all variables are taken from the Our World In Data website (<https://ourworldindata.org/>).

#### 3.3. Data analysis

The data was input into three different regression models. The analysis results of the multiple linear regression model and the MGWR

model were compared to test for spatial heterogeneity in the effects of institutional-social-ecological factors affecting case-fatality rate of COVID-19 and identify the institutional-social-ecological factors on the case-fatality rate of COVID-19. Additionally, the GWR model was used to test the robustness of the results.

The first regression model is the multiple linear regression model, which is the most often used statistical technique in the analysis of factors identification. It works by using several explanatory variables to predict the outcome of a response variable and can be seen as an extension of the ordinary least-squares (OLS) regression. The multiple linear regression model is expressed by Eq. (1).

$$y_i = \beta_0 + \beta_1 x_{i1} + \beta_2 x_{i2} + \dots + \beta_p x_{ip} + \epsilon \quad (1)$$

In Eq. (1),  $y_i$  is the dependent variable;  $x_{ij}$  represents the independent variables;  $\beta_0$  is the intercept (constant term);  $\beta_p$  represents the slope coefficients for each independent variable;  $\epsilon$  is the model's error term (also known as the residuals).

The multiple linear regression model has limited utility in cross-regional studies, as it assumes changes across space to be universal, which is not always the case in every spatial context. The Ordinary least-squares (OLS) regression is a simple global fitting method, though it might lose spatial non-stationarity when used to carry out cross-regional analysis [52]. Therefore, a geographically weighted regression (GWR) model provides an alternative method to analyze and model the complex spatial variations in local parameter estimates [52,53,54]. The GWR model is an extension of the traditional linear regression model that provides for local variations of parameter estimates to incorporate spatial heterogeneity in different regions [55]. The GWR model is expressed by Eq. (2).

$$y_i = \beta_{0j} + \beta_{1j} x_{i1} + \beta_{2j} x_{i2} + \dots + \beta_{pj} x_{ip} + \epsilon \quad (2)$$

In Eq. (2), the parameter estimates are now indexed by the  $j$ th location.

Although the GWR model accounts for the impact of spatial variation on parameter estimation, it is subject to two limitations; multiple hypothesis testing may produce false positives [56] and there is an accuracy problem stemming from the univariate scale assumption through using a single bandwidth for each variable [57]. To address these limitations, Fotheringham et al. [58], Yu et al. [57] and Oshan et al. [59] proposed the multi-scale geographically weighted regression (MGWR) model. The MGWR model allows variables to have different spatial smoothing levels, making their bandwidth specific and thus solving the issue that the optimal bandwidth limit of all variables needs to be the same in the GWR model. The MGWR model is expressed by Eq. (3).

$$y_i = \sum_{i=1}^k f_{ij} + \epsilon \quad (3)$$

In Eq. (3),  $f_{ij}$  is a smoothing function (i.e., spatial weight) applied to the  $i$ th independent variable at location  $j$ .

Compared with the GWR model, the MGWR model has been shown to have a better overall model performance by introducing multiple scales; specifically, there is a stark difference in the bandwidth values [58]. However, a case study found that the parameter estimates of the MGWR model were lower than those of the GWR model [60]. Therefore, in the present study, MGWR and GWR are taken as the main analysis model and the robustness check model, respectively.

## 4. Results

### 4.1. Descriptive statistics

According to the research materials and data collection method, a total of 134 valid pieces of data were collected from 134 countries and regions. The collinearity amongst independent variables was tested by the variance inflation factor using the collected data. As shown in

Table 2, no significant collinearity was found amongst the independent variables (the VIF value of each variable is less than 10). Therefore, in the multiple linear regression, GWR and MGWR models were able to be used in this study and the variables did not require further processing.

Table 3 presents the descriptive statistics of the data values of all variables included in the study. According to the descriptive statistics of "liberal democracy", there were significant differences in the level of democracy amongst the countries in the sample. As shown in Fig. 5.1, the democratic levels of countries in Asia, the Middle East and northern Africa was low, those of most countries in Southeast Asia and Southern Africa were medium-low, those of most countries in South America were medium-high, and those of countries in Western Europe, North America and Oceania were generally high.

According to the descriptive statistics of "gross domestic product (GDP)", GDP varied greatly between countries. As shown in Fig. 5.2, the GDPs of the United States and China was far ahead of other countries, followed by the United Kingdom, France, Germany, and India. The GDPs of developed countries in Western Europe, Canada, Russia, and Australia were in the mid-range of the sample, whilst the GDPs of some countries in Southeast Asia, Africa, and most countries in Eastern Europe were amongst the lowest in the world.

There was a significant difference in the number of nurses per 1000 people in different countries. The countries with the lowest value had only 0.1119 nurses per 1000 people, whereas those countries with the highest value had 18.3493 nurses per 1000 people. As can be seen in Fig. 5.3, the countries with the highest values for "nurses per 1000 people" were mainly developed countries. Meanwhile, the values for "nurses per 1000 people" in Eastern Europe and Brazil were at the medium-high level, Russia and some countries in Southeast Asia were at medium level, some countries in Asia, America and Southern Africa were at the medium-low level, and most African countries were at the lowest level.

According to the standard deviation of "press freedom", there were significant differences in the control of news reports amongst countries: the maximum and minimum "press freedom" values were 81.45 and 6.72, respectively. As shown in Fig. 5.4, most western developed countries do not strictly control the freedom of news reporting, while China and the Middle East exert tight control over news reporting.

The maximum value of "COVID-19 testing policy" was 4, the minimum value was 1, and the average value was 3.5670646. Most countries have adopted extensive COVID-19 testing policies; interestingly, Canada, Japan, Sweden, the Central African Republic, Iran and other countries have completely abolished their COVID-19 testing policies during the Omicron variant epidemic period (see Fig. 5.5).

According to the descriptive statistics of "COVID-19 contact tracing policy", there were significant differences in the intensity of COVID-19 tracking across the sampled countries. As indicated in Fig. 5.6, China, Australia, New Zealand, Saudi Arabia, Finland, and other countries have adopted strict COVID-19 contact tracing policies. The intensity of COVID-19 contact tracing in most North American, Western European, and Southeast Asian countries was at the medium level, whereas Brazil and half of the African countries sampled carried out essentially no tracking of COVID-19 transmission.

According to the descriptive statistics of "economic support policy", the economic support provided to citizens during the Omicron variant epidemic period differed amongst the sampled countries. As shown in Fig. 5.7, China, Japan, Austria, Germany, Romania, Ireland, Iceland, Pakistan and Malaysia offered robust economic support. Contrastingly, the United States, Paraguay, Chile, Australia, Philippines, Vietnam, Cambodia and Middle Eastern and African countries basically did not provide economic support for the people during the Omicron variant epidemic period.

The maximum value of "COVID-19 vaccination policy" was 6, the minimum value was 1, and the average value was 5.7872404. These figures indicate that although the vaccination policies of various countries were different, most countries have adopted extensive vaccination

policies during the Omicron variant epidemic period. As shown in Fig. 5.8, some countries in Africa, the Middle East and Southeast Asia have only partially promoted and implemented vaccination policies; notably, Afghanistan and Eritrea almost did not promote COVID-19 vaccinations in the Omicron variant epidemic period.

The maximum value of “population density” was 8383.010, the minimum value was 2.169, and the standard deviation was 759.595834, which indicated that there were significant differences in population density amongst the sampled countries. As shown in Fig. 5.9, the population density of Asia and Western Europe was greater than that of other regions in the world.

According to the descriptive statistics of “age dependency ratio”, there were significant differences in the ratio of the non-labor to labor populations amongst countries. As shown in Fig. 5.10, in Afghanistan, Pakistan, Iraq, Japan and some countries in Central Africa, the dependent populations were far higher than the labor population. As such, the working populations in these countries were placed under greater pressure during the pandemic.

According to the descriptive statistics of “share of the population using the Internet”, there were significant differences in the popularity of the Internet across the sampled countries. As shown in Fig. 5.11, the Internet popularity rates in Canada, most European countries, and Oceania were generally high, whilst the Internet popularity rates in China, the Americas, and most Southeast Asian countries were at the middle level in the world. Meanwhile, the Internet popularity rates in most African countries were significantly lower than the world average.

The average value of “COVID-19 case-fatality rate” was 0.00132588, thus indicating that the global COVID-19 case-fatality rate remained at a low level during the Omicron variant epidemic period, though the highest COVID-19 case-fatality rate was 0.015607. As shown in Fig. 5.12, the COVID-19 case-fatality rates in Moldova, Bosnia and Herzegovina, Eritrea, Suriname, Guyana, and Namibia far exceeded the world average.

#### 4.2. Spatial heterogeneity test

The goodness of fit of the multiple linear regression and MGWR models were compared to test for spatial heterogeneity in institutional-social-ecological factors affecting the case-fatality rate of COVID-19. As shown in Table 4, the MGWR model improved the R2 from 0.158 to 0.470. Moreover, the AICc value of the MGWR model was significantly lower than that of the multiple linear regression model, thus indicating that the MGWR model was better able to measure the COVID-19 case-fatality rate. Compared with residual sum of squares of the multiple linear regression model and the MGWR model, the residual sum of squares of the MGWR model was smaller, suggesting that it can obtain regression results closer to the true value with fewer parameters. The results show that the local model (MGWR model) exhibits better goodness of fit than the global ordinary least squares (OLS) model. Therefore, it can be concluded that there is significant spatial heterogeneity in the impact of institutional-social-ecological factors on the case-fatality rate

**Table 2**  
Variance inflation factor (VIF).

Name of variables	Variance Inflation Factor (VIF)
Liberal democracy	5.025
Gross domestic product (GDP)	1.245
Nurses per 1000 people	3.196
Press freedom	4.011
COVID-19 testing policy	1.034
COVID-19 contact tracing policy	1.325
Economic support policy	1.270
COVID-19 vaccination policy	1.374
Population density	1.141
Age dependency ratio	2.381
Share of the population using the Internet	4.619

of COVID-19. The MGWR model is a better choice for this case study, with 47.0% of the variation of the COVID-19 case-fatality rate capable of being explained by the institutional-social-ecological variables in the MGWR model.

#### 4.3. Scale analysis

Different influencing factors exhibit different degrees of heterogeneity at different scales, that is, within a certain range, the effect size is similar, but beyond the range, the effect size is significantly different [61,62]. The MGWR model allows for the inclusion of multiple action scales between independent variables to reduce noise and bias in the regression coefficients, thus enhancing the model's robustness. The regression results of the MGWR model showed that Gross domestic product (GDP), Press freedom, COVID-19 testing policy, COVID-19 vaccination policy, Population density, and Age dependency ratio had varying degrees of significance for COVID-19 case-fatality rate. As shown in Table 5, the bandwidth of significant variables is shown as follows: (1) The bandwidths of “COVID-19 testing policy” and “population density” were 46 and 72, which are micro-scale variables, whilst the scale is close to that of 1–2 continents. This shows that the variables had great spatial heterogeneity; once heterogeneity exceeds the range, the coefficient will change dramatically. (2) “gross domestic product (GDP)”, “press freedom” and “COVID-19 vaccination policy” are macro-scale variables, their bandwidth accounts for 83.6%, 72.4% and 72.4% of the sample size respectively. This scale is close to the number of countries studied, indicating that they are relatively stable in space. (3) The bandwidth of the age dependency ratio reached 133, which is a global variable with little spatial heterogeneity.

#### 4.4. Analysis of coefficient spatial pattern

The institutional-social-ecological factors affecting the COVID-19 case-fatality rate were identified through the MGWR model. As shown in Table 6, of the 11 institutional-social-ecological factors, six key factors were identified based on the ascending effect size: COVID-19 vaccination policy, age dependency ratio, press freedom, gross domestic product (GDP), COVID-19 testing policy, population density. Hypothesis H2, H4, H5, H8, H9, H10 were supported by the findings in this study.

The coefficient of gross domestic product (GDP) was between  $-0.58564030200$  to  $-0.64405422000$ , and the mean value was  $-0.60906084000$  (see Table 6), whilst the coefficient value indicated that its influence intensity is in the middle. However, its impact scope was the smallest: As shown in Fig. 6.1, the impact of GDP on the COVID-19 case-fatality rate was significant only in Cape Verde, Gambia, Senegal and Sierra Leone. The GDP of these four countries ranked low amongst 134 countries and regions, which showed that although GDP has no significant impact on the case-fatality rate of COVID-19 in most countries, the public health issues during the COVID-19 pandemic still constitute a major challenge for those countries that are particularly poor, especially as the COVID-19 pandemic also negatively impacts production, daily life, imports and exports, and other economic activities.

Strict media control can reduce the case-fatality rate of COVID-19. The coefficient of press freedom was between  $-0.42604117200$  and  $-0.48076357800$ , whilst the average coefficient and standard deviation were  $-0.45844197900$  and  $0.01458790221$ , respectively (see Table 6). Moreover, the influence intensity of the factor was at the middle level, with little difference between the regions. As shown in Fig. 6.2, Latin America confirmed the impact of press freedom on the case-fatality rate of COVID-19. The degree of control exerted over the media by the governments of these countries was at the middle level globally, though it was notably different from countries in Western Europe, the United States and Canada, which have more press freedom. Meanwhile, as Latin American countries have a large number of local forces, such as drug



**Table 3**  
Descriptive statistics of the variables (n = 134).

	Minimum	Maximum	Mean	Std. Deviation
Liberal democracy	0.010	0.878	0.42232	0.266992
Gross domestic product (GDP)	1,632,000,000	19,294,500,000,000	579,677,976,119.402800	2,152,467,294,738.634
Nurses per 1000 people	0.1119	18.3493	4.589460	4.3965785
Press freedom	6.72	81.45	33.9497	15.97275
COVID-19 testing policy	1.00000	4.00000	3.5670646	0.62770266
COVID-19 contact tracing policy	1.00000	3.00000	2.1286929	0.68434340
Economic support policy	1.00000	3.00000	1.6218330	0.62449465
COVID-19 vaccination policy	1.00000	6.00000	5.7872404	0.59582024
Population density	2.169	8383.010	215.36250	759.595834
Age dependency ratio	20.34	105.44	58.7426	15.89463
Share of the population using the Internet	1.30891	99.70150	57.8199296	28.95486488
COVID-19 case-fatality rate	0.000001	0.015607	0.00132588	0.002656318

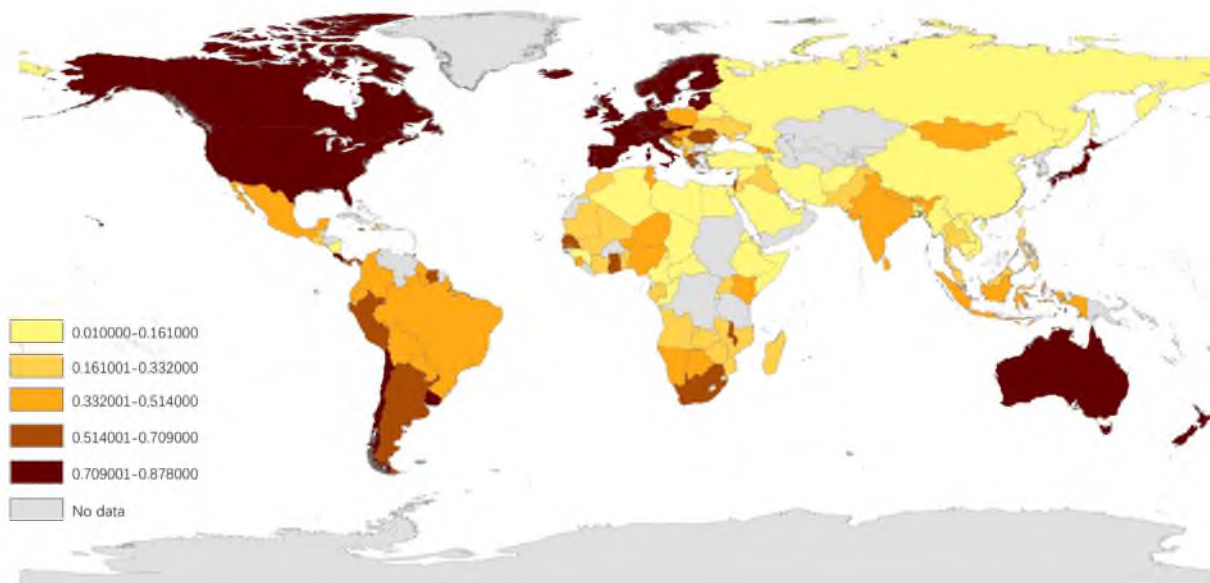


Fig. 5.1. Liberal democracy.

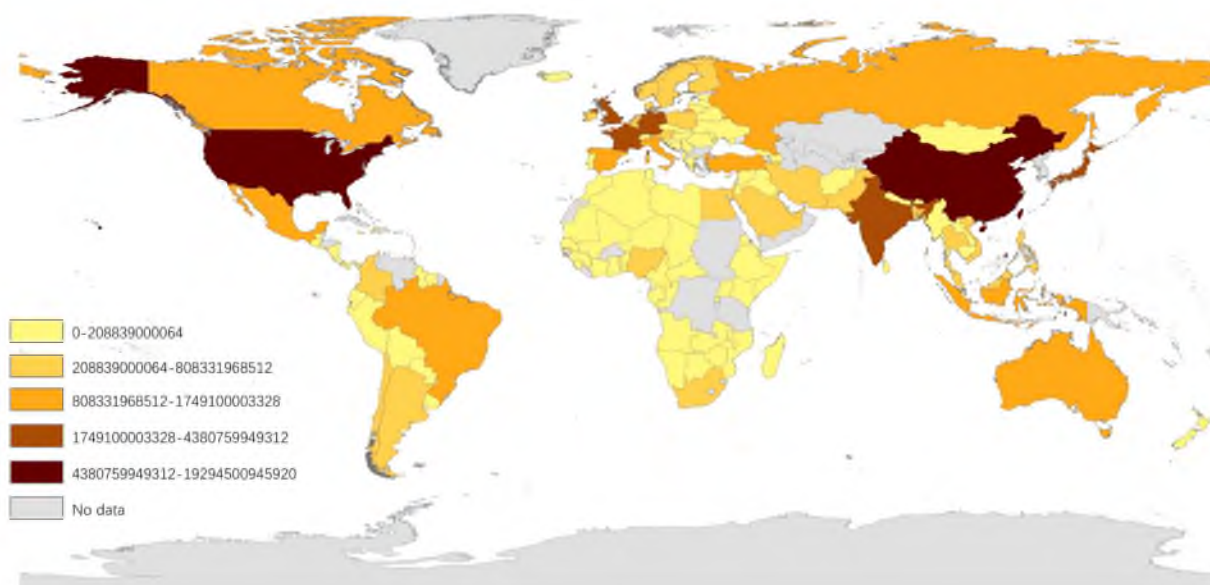


Fig. 5.2. Gross domestic product (GDP).

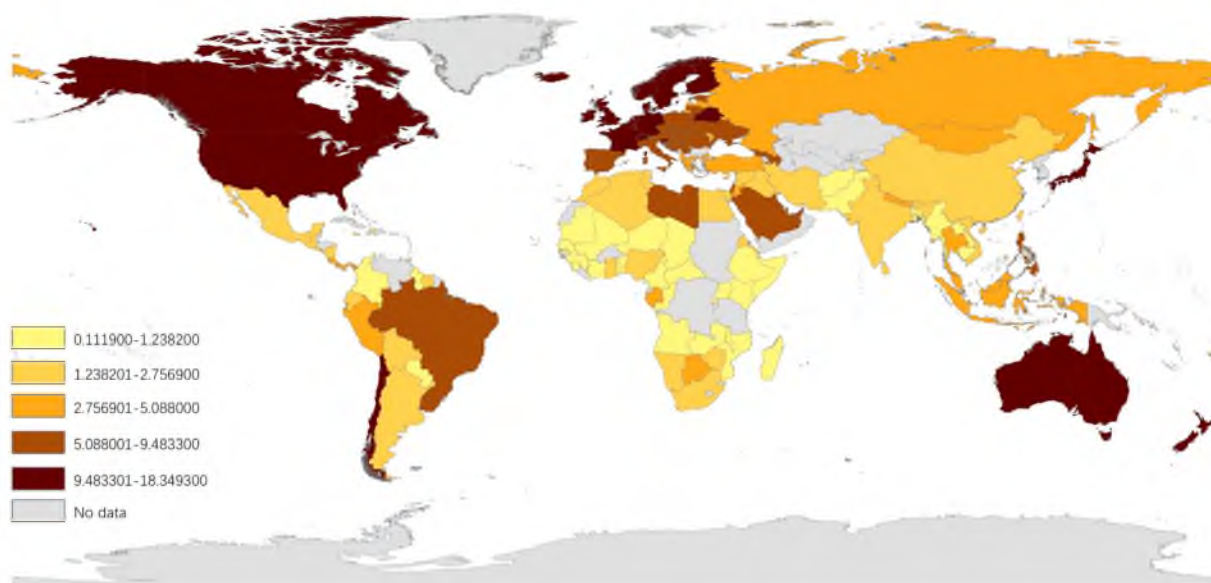


Fig. 5.3. Nurses per 1000 people.

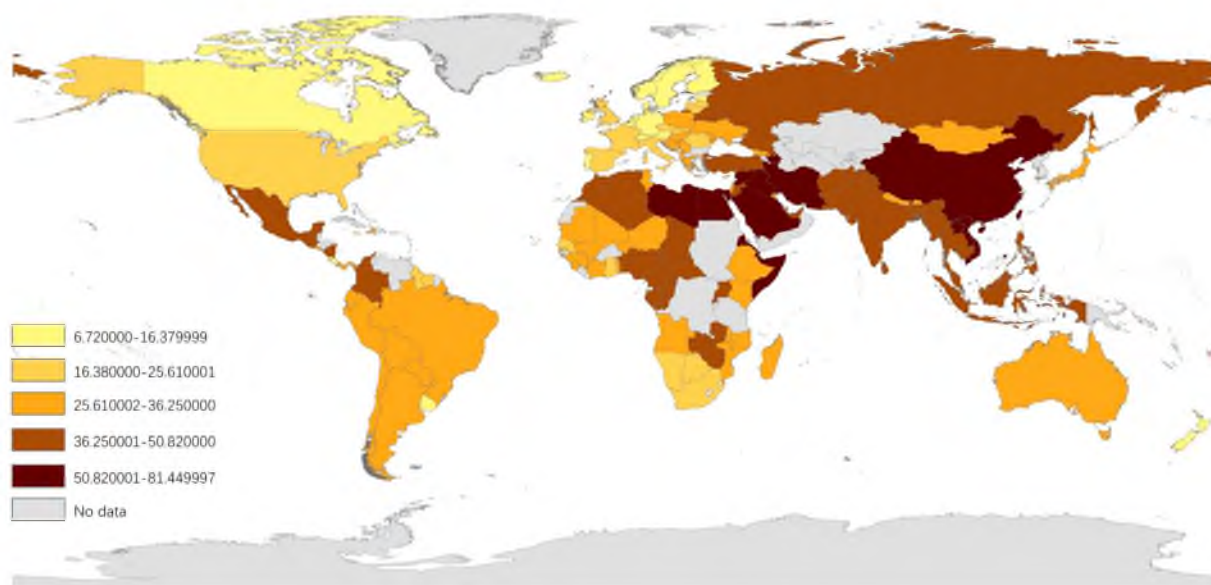


Fig. 5.4. Press freedom.

barons and gangs, the authority of governments in such countries is weaker than the authority of governments in Western developed countries with more press freedom (the governments cannot even govern those individuals who are subordinate to local forces). Under the influence of the pandemic, some local forces are likely to issue other measures against the COVID-19 pandemic restriction policies to people through their media in an effort to safeguard their own interests. In other countries with less media control but higher government authority, although some people may believe fake news and misinformation, leading them to not comply with the COVID-19 pandemic restriction policies, the possibility of mass disobedience of the government's pandemic restriction policies is low.

The provision of an extensive COVID-19 testing policy can reduce the case-fatality rate of COVID-19. As shown in Table 6, the coefficient of COVID-19 testing policy ranged from  $-0.36471393500$  to  $-1.15629738900$ , whilst the mean value was  $-0.82616776156$ . The impact intensity amongst the identified factors was high and there were

clear differences between the regions sampled. As shown in Fig. 6.3, the spatial distribution of the effect size of COVID-19 testing policy showed a gradually increasing trend from North to South America. The COVID-19 testing policy had an impact on the case-fatality rate of COVID-19 from two aspects. On the one hand, early COVID-19 case detection can allow patients to receive treatment in time to prevent the aggravation of the condition and possible death. Compared with countries in Latin America, the public health conditions in the United States and Canada are superior. Therefore, the COVID-19 testing policy had a stronger effect on the COVID-19 case-fatality rate in Latin American countries. On the other hand, a more extensive COVID-19 testing policy can identify more COVID-19 cases; the broader the criteria for testing, the wider the denominator, and the lower the proportion of positive tests.

The implementation of an extensive COVID-19 vaccination policy can reduce the case-fatality rate of COVID-19, which confirms the role of COVID-19 vaccination in alleviating the symptoms of COVID-19. The

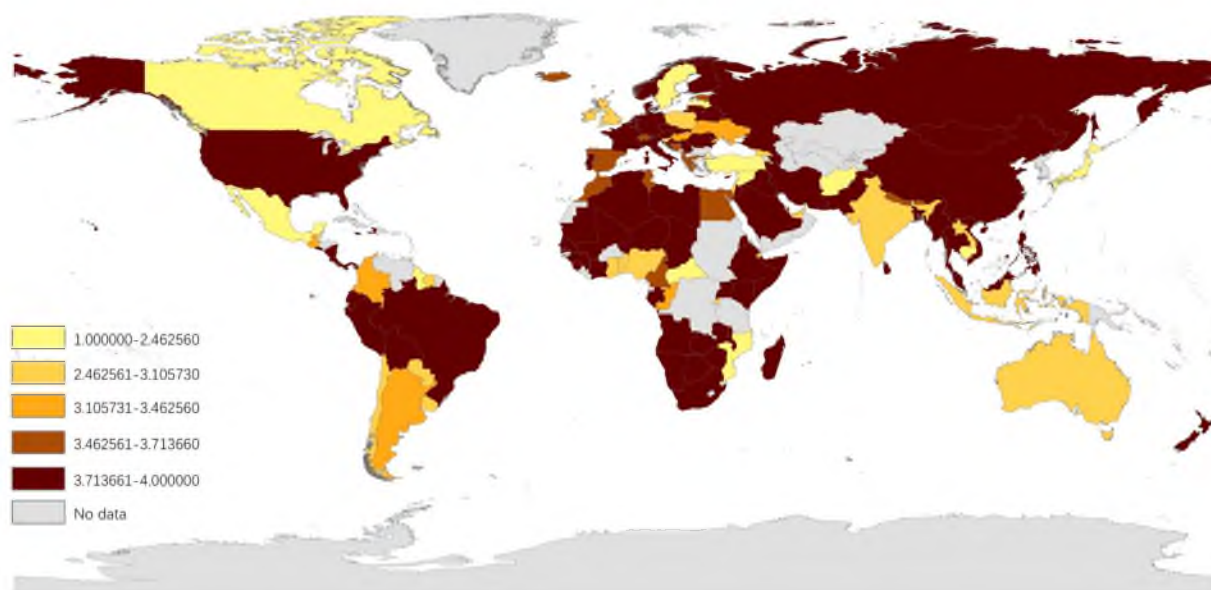


Fig. 5.5. COVID-19 testing policy.

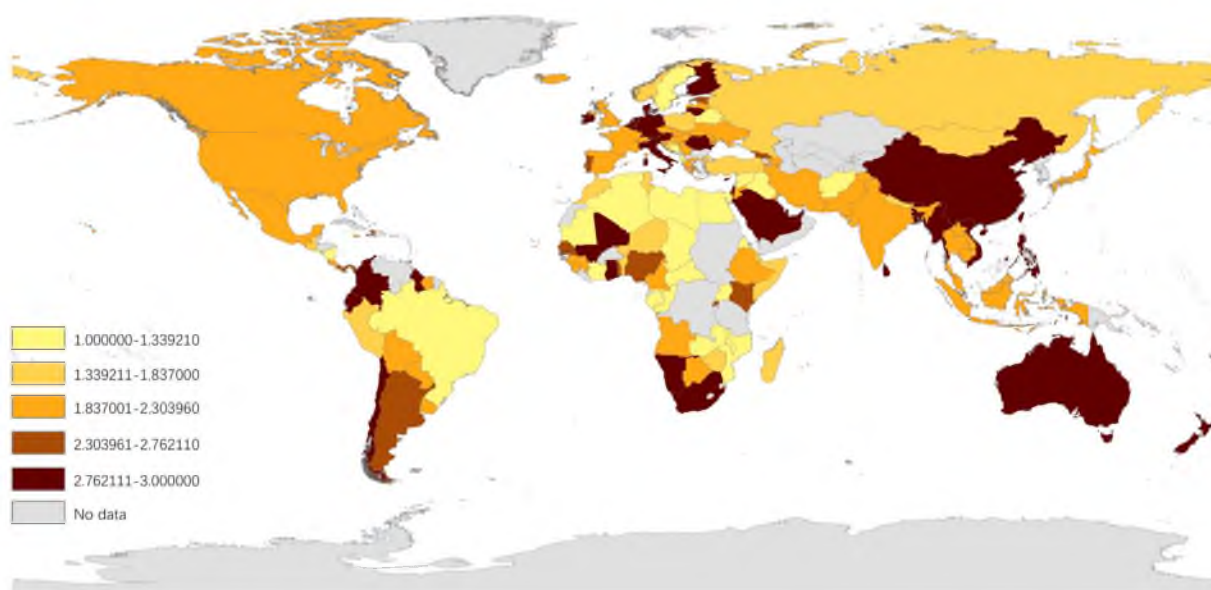


Fig. 5.6. COVID-19 contact tracing policy.

coefficient of COVID-19 vaccination policy ranged from  $-0.19175878000$  to  $-0.21301460300$ , whilst the mean value was  $-0.20028184966$ . Amongst the all identified factors, its influencing intensity was the lowest. During the Omicron variant epidemic period, the COVID-19 vaccination rate reached a high level in most countries. Therefore, the vaccination policy was only significant in those regions where the COVID-19 vaccination rate and the popularization rate of COVID-19 vaccination policy were low. As shown in Fig. 6.4, COVID-19 vaccination policy was significant in Eastern Europe, the Middle East, and some African countries, with an increasing trend observed from north to south. By comparing with Fig. 5.8 and Fig. 6.4, it can be seen that some of these countries had poor COVID-19 vaccination policies, such as Belarus, Egypt, Eritrea, Somalia, Chad, and the Central African Republic. Moreover, the COVID-19 vaccination rate in these countries was low: except for Greece and Saudi Arabia, the vaccination rate in other countries was below 70%. Notably, the vaccination rates in Yemen

and Madagascar were just 2.126% and 4.503%, respectively. According to Fig. 5.12, the COVID-19 case-fatality rate in countries with low COVID-19 vaccination rates in Eastern Europe, the Middle East and Africa were significantly higher than those in countries with high COVID-19 vaccination rates. Therefore, in those countries with low COVID-19 vaccination rates, the government still needs to introduce an extensive COVID-19 vaccination policy to improve the COVID-19 vaccination rate.

The coefficient of population density was  $0.59194488200$  to  $1.69460899600$ , whilst the mean value was  $1.24573619511$  and the standard deviation was  $0.29795278472$ . It should be highlighted that this is the factor with the highest effect size on the case-fatality rate of COVID-19, and also that there were significant regional differences in the sample. As shown in Fig. 6.5, the impact of population density on COVID-19 case-fatality rate can mainly be seen in the Americas, Western Europe, and northwest Africa. Although most studies have shown that

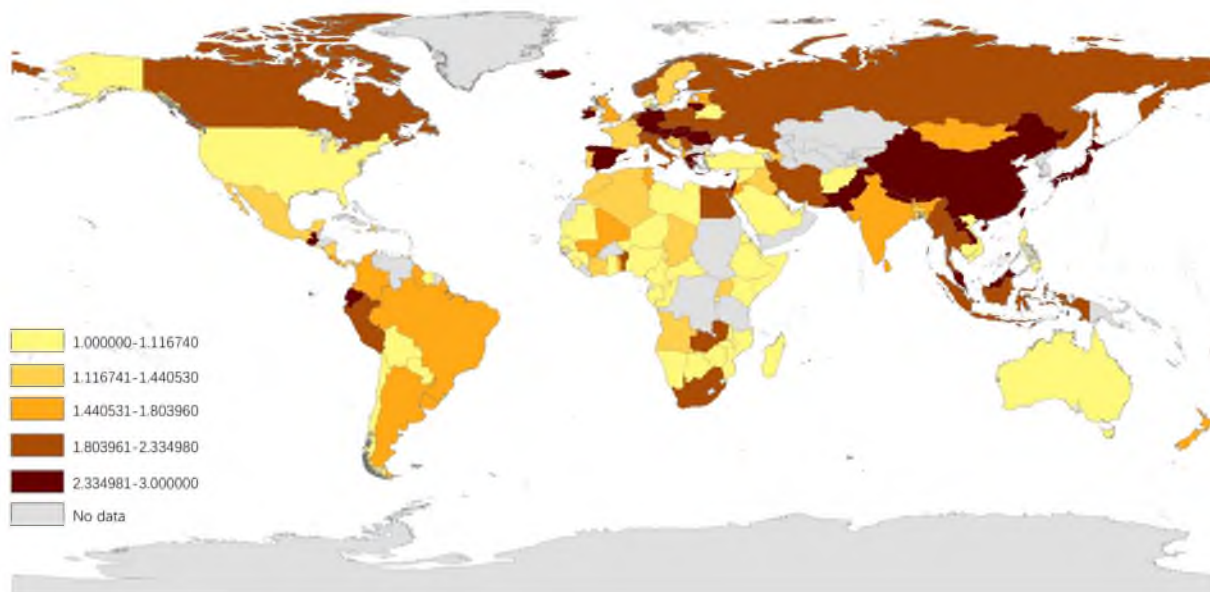


Fig. 5.7. Economic support policy.

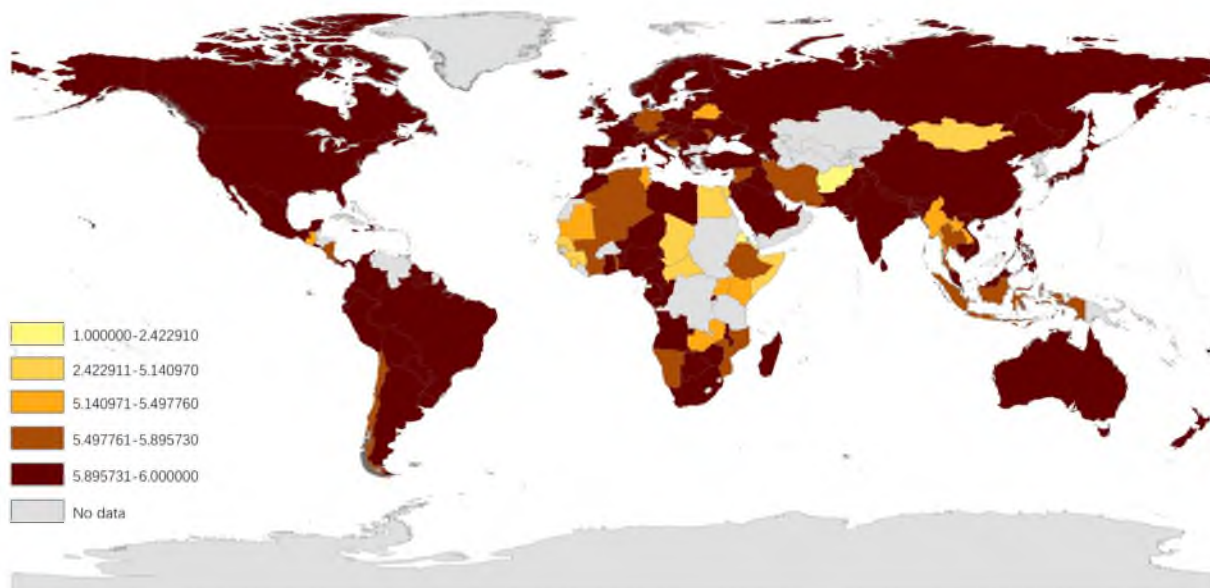


Fig. 5.8. COVID-19 vaccination policy.

population density is a significant factor impacting COVID-19 transmission, there is no research to prove that population density impacts the severity of COVID-19 symptoms. However, it can assuredly be said that if those countries and regions with higher population densities do not implement effective measures to deal with COVID-19 pandemic, public health resources come under high pressure. Although the public health resources of the United States, Canada and developed countries in Western Europe are world-leading in terms of nurses per 1000 people, the infection rates of these countries were also higher than most counties in the world. COVID-19 placed the public health systems of various countries under significant strain; when the public health system is overloaded, some infected people cannot be treated in time, resulting in death.

The coefficient of age dependency ratio ranged from  $-0.29046927900$  to  $-0.30449428200$ , whilst the mean value was  $0.29828834802$ , meaning that its effect size was only higher than COVID-19 vaccination policy. However, the impact of this factor was

significant globally (see Fig. 6.6). In contrast with the findings presented in most of the existing research, this study showed that the higher the proportion of young adults in the population, the higher case-fatality rate of COVID-19 in various countries. Compared with the regression results and data (see Fig. 6.6 and Fig. 5.10), countries with small working populations relative to the entire population were more sensitive to changes in the age dependency ratio. This may indicate that the main risk people of case-fatality of COVID-19 were still the elderly and minors with low immunity during the Omicron variant epidemic period, although the main COVID-19 transmission group was the young and middle-aged people. Those people with low immunity or impaired immune systems were likely to be infected by the working people and eventually die.

#### 4.5. Robustness checks

The variables of the study were substituted into the GWR model to

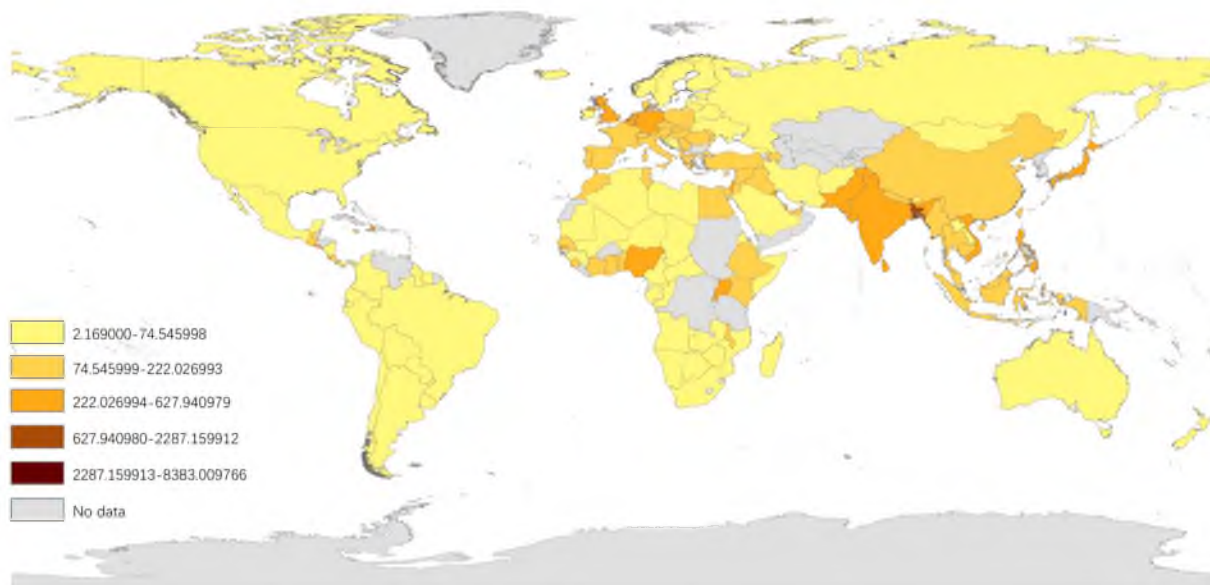


Fig. 5.9. Population density.

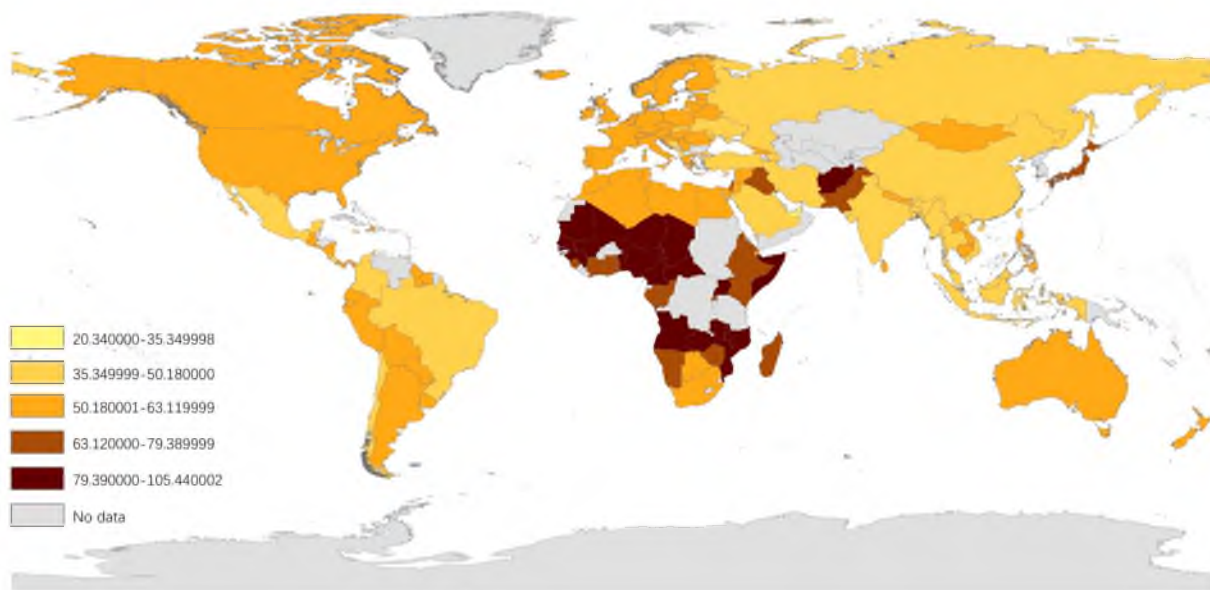


Fig. 5.10. Age dependency ratio.

determine the robustness of the results. As shown in Table 7, the GWR model is slightly inferior to the MGWR model in terms of goodness of fit, and the bandwidth of each variable is 111. Comparing the results of the MGWR model and GWR model (see Table 6 and Table 8), the six institutional-social-ecological factors identified by the MGWR model that affect the case-fatality rate of COVID-19 are also significant in the GWR model, whilst the effect directions of these six factors are also the same in the two models. Therefore, the research results are proved to be robust.

### 5. Discussion

The MGWR model was used to identify the factors affecting the case-fatality rate of COVID-19. The results show that:

- (1) Amongst the ecological factors, gross domestic product (GDP) and press freedom significantly impacted the case-fatality rate of COVID-19. The result of gross domestic product on the case-fatality rate showed that, even though the case-fatality rate of COVID-19 has decreased to a low level, COVID-19 is still a significant challenge to national public health in countries already grappling with extreme poverty. On the one hand, countries in extreme poverty struggle to provide adequate medical conditions for COVID-19 patients; on the other hand, it is difficult for these countries to deal with the contrary aims of economic development and COVID-19 pandemic restriction policies (i.e., stay at home requirements, workplace closures). Therefore, these countries can seek medical and health assistance from the World Health Organization or other countries to reduce the case-fatality rate of COVID-19. Press freedom represents the restrictions countries place on media and civil liberties, that is, the more loose

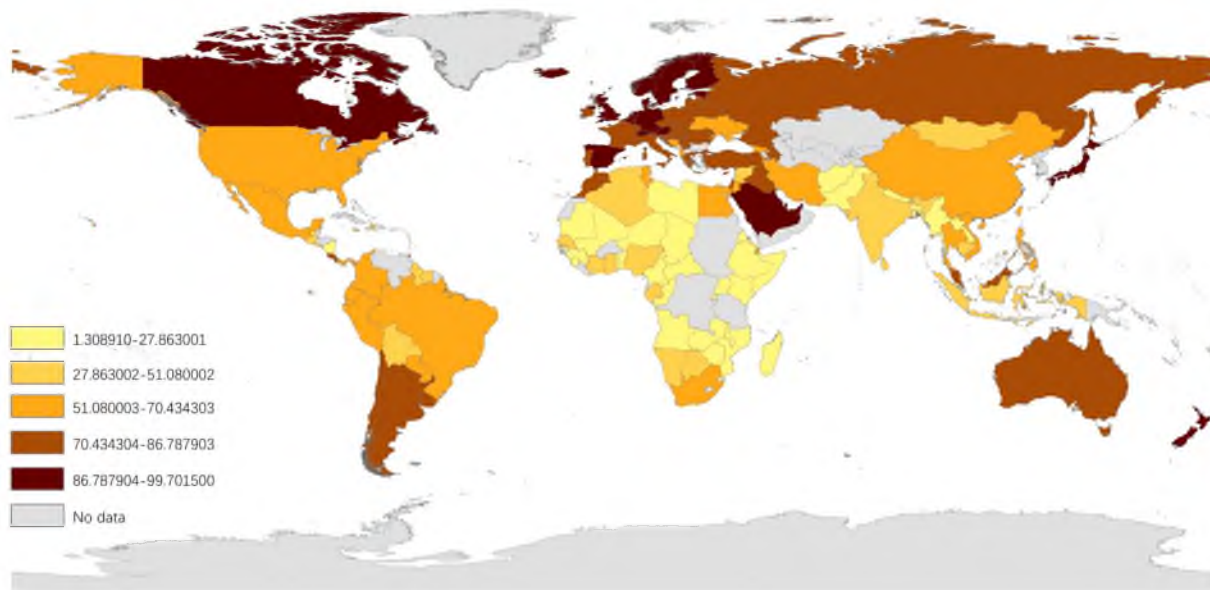


Fig. 5.11. Share of the population using the Internet.

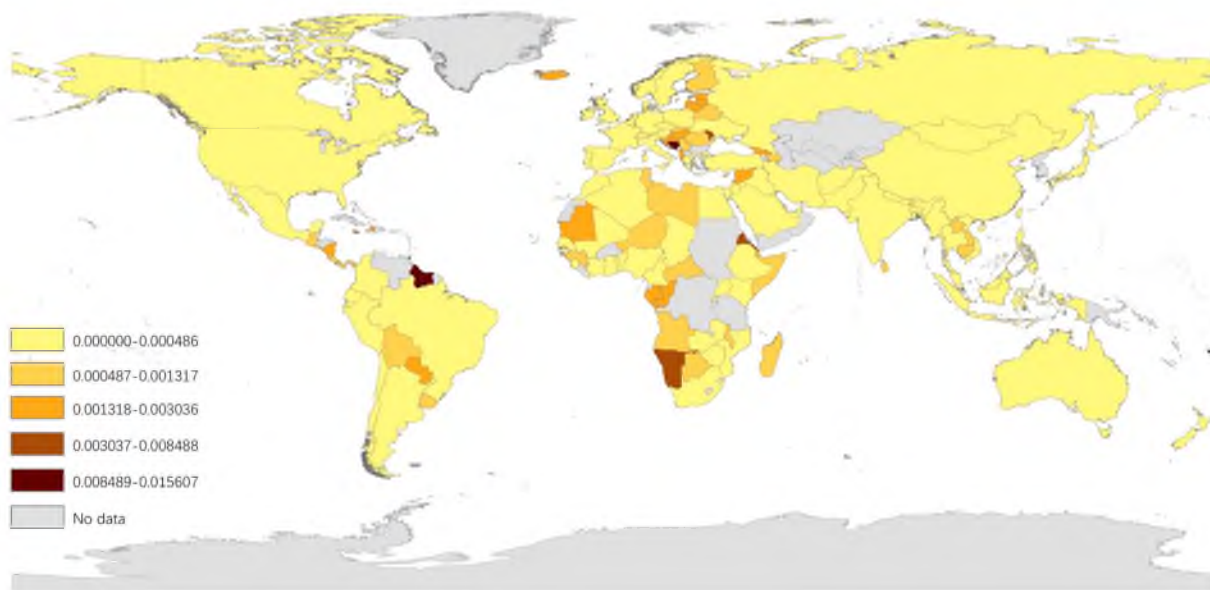


Fig. 5.12. case-fatality rate of COVID-19.

**Table 4**  
Comparison of multiple linear regression, GWR and MGWR model indicators.

Model Indexes	Multiple Linear Regression Model	MGWR Model
R <sup>2</sup>	0.158	0.470
AICc	386.277	372.773
Residual sum of squares	112.839	71.063

media censorship, the country is more likely to respond with self-control public health measures without stringent interventions. Pandemic control and prevention depend more on the choice of individuals. Therefore, in countries with less government control, people are more likely to choose to trust the media and respond differently to the pandemic, thus increasing the case-fatality rate of COVID-19. This conclusion was also put forward by Karabulut

**Table 5**  
Bandwidth of the MGWR model.

Variable	MGWR model
Gross domestic product (GDP)	112
Press freedom	97
COVID-19 testing policy	46
COVID-19 vaccination policy	97
Population density	72
Age dependency ratio	133

et al. [18]. Yao et al. [22] believed that temporarily mandated measures responding to pandemics should be separated from the suppression of citizens' democratic rights and freedoms.

**Table 6**  
Statistical description of the MGWR regression coefficient.

Variable	Mean	STD	Min	Median	Max
Gross domestic product (GDP)	-0.60906084000	0.02476642766	-0.58564030200	-0.60327441900	-0.64405422000
Press freedom	-0.45844197900	0.01458790221	-0.42604117200	-0.46034739800	-0.48076357800
COVID-19 testing policy	-0.82616776156	0.22135634398	-0.36471393500	-0.87866172300	-1.15629738900
COVID-19 vaccination policy	-0.20028184966	0.00645796526	-0.19175878000	-0.19854267100	-0.21301460300
Population density	1.24573619511	0.29795278472	0.59194488200	1.30149847000	1.69460899600
Age dependency ratio	-0.29828834802	0.00361003831	-0.29046927900	-0.29937729700	-0.30449428200



**Fig. 6.1.** The impact of GDP on the case-fatality rate of COVID-19.



**Fig. 6.2.** The impact of press freedom on the case-fatality rate of COVID-19.

(2) In the governance system, COVID-19 testing policy and COVID-19 vaccination policy exerted a significant influence on the case-fatality rate of COVID-19. Early detection of COVID-19 can help infected people receive timely treatment and prevent the

disease from worsening and leading to death. Moreover, when COVID-19 infections are detected early, some individuals will actively or passively avoid transmitting COVID-19 to others, especially those with low immunity. Similar to Liang et al. [43],



Fig. 6.3. The impact of COVID-19 testing policy on the case-fatality rate of COVID-19.

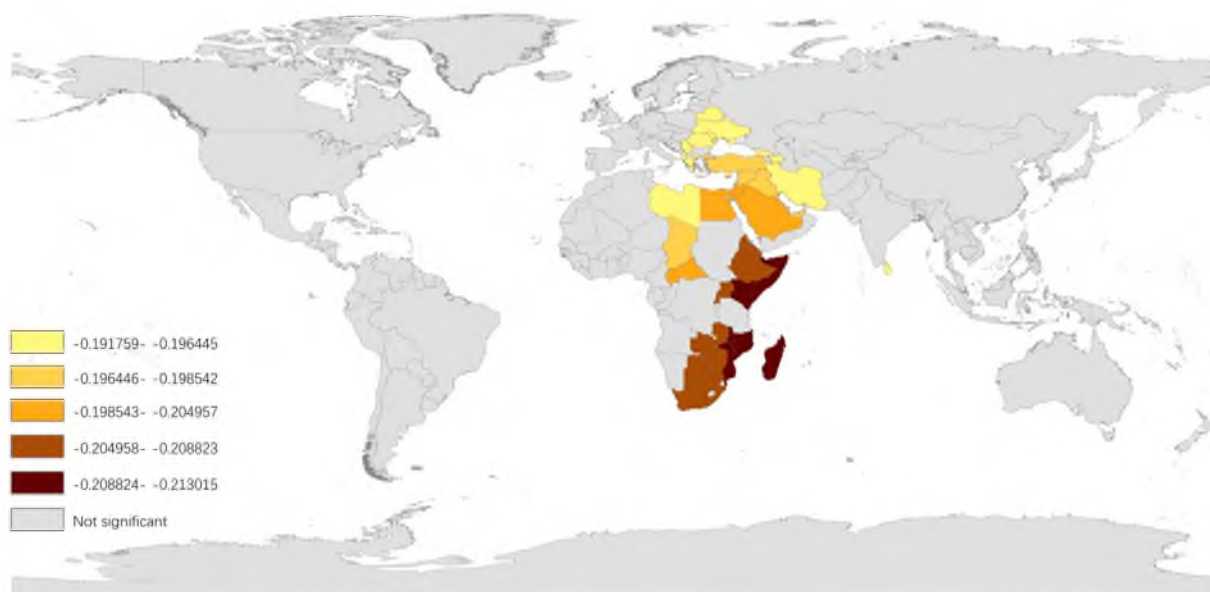


Fig. 6.4. The impact of COVID-19 vaccination policy on the case-fatality rate of COVID-19.

this study proved that COVID-19 vaccines can effectively reduce the severity of COVID-19 symptoms, thus reducing the incidence rates of severe cases and case-fatality rates. Therefore, many extreme poverty countries with low COVID-19 vaccination rates can effectively reduce the case-fatality rate of COVID-19 and alleviate public health system and national economic pressures through international assistance in the form of COVID-19 vaccine provision. In addition, groups with low immunity, such as the elderly and patients with respiratory diseases, should be vaccinated with a COVID-19 vaccine to improve their immunity against COVID-19 and prevent infection and severe cases.

- (3) For actors, population density and age dependency ratio significantly influenced the case-fatality rate of COVID-19. The public health systems of countries with high population density typically are under greater pressure as COVID-19 transmits more rapidly in high-density environments [63,46,64]. Under the dual

effect of population density, COVID-19-infected people cannot be treated in time and can easily infect vulnerable people. Therefore, countries with high population densities should avoid people gathering and interacting through the implementation of COVID-19 pandemic restriction policies and build more public health facilities for the treatment of COVID-19 patients. According to the effect of age dependency ratio on the case-fatality rate, a larger working population will increase the case-fatality rate of COVID-19, though the fatalities mainly seem to be dependants with low immunity. Compared with the dependant population, the working population is usually more mobile, especially when the movement restrictions were lifted in most countries during the Omicron variant epidemic period. Such population movement will lead to rapid COVID-19 transmission [65,46,64]. In those countries with a higher proportion of the working population (relative to the total population), people with low immunity are



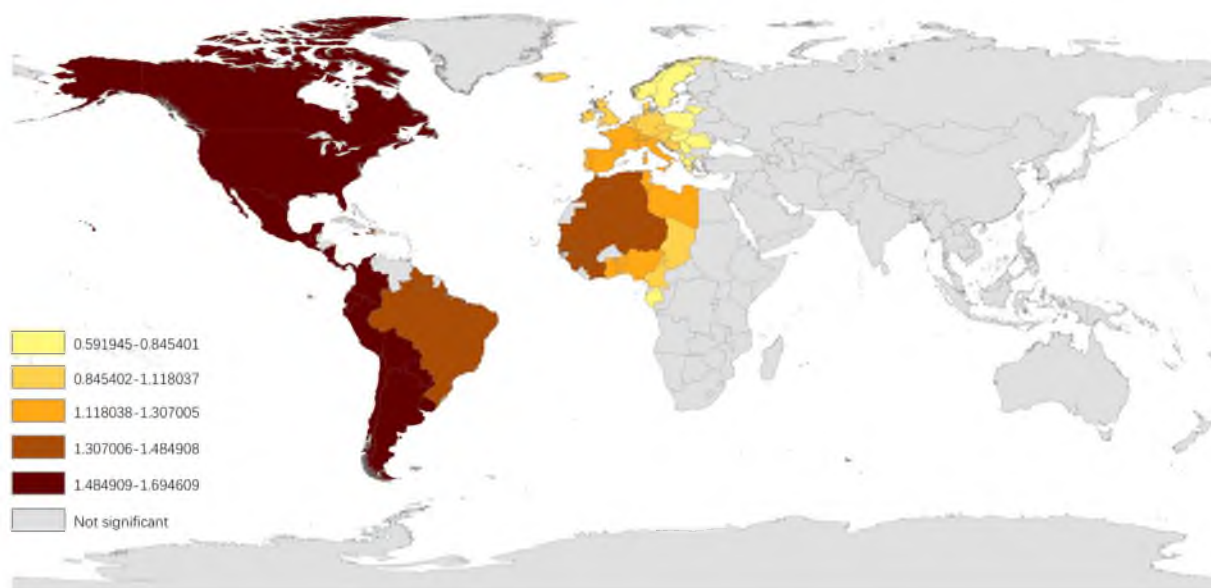


Fig. 6.5. The impact of population density on COVID-19 case-fatality rate.

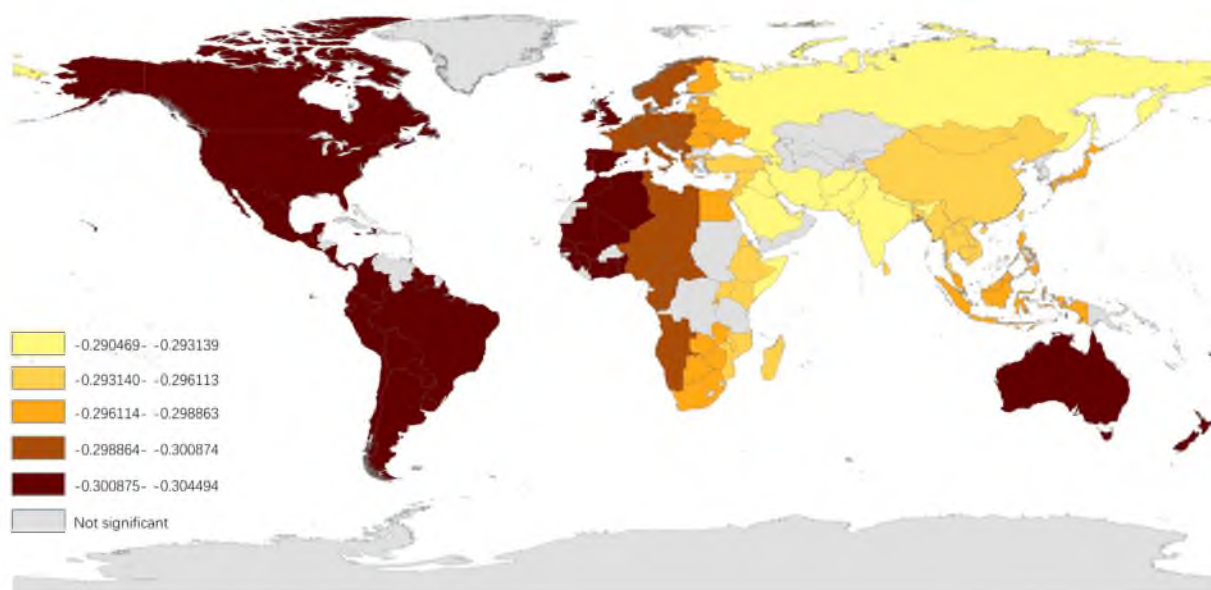


Fig. 6.6. The impact of age dependency ratio on COVID-19 case-fatality rate.

**Table 7**  
Diagnostic Information of the GWR model.

Model Indexes	GWR model
R <sup>2</sup>	0.421
AICc	373.963
Residual sum of squares	77.638
Bandwidth	111

more likely to be infected with COVID-19 (Giangreco [66] made a similar point in the Italian study). Therefore, in some countries with aging populations or low COVID-19 vaccination rates, the government should implement COVID-19 restriction policies to

reduce population mobility as far as possible to avoid COVID-19 transmission, actively popularize COVID-19 vaccination, and ensure basic production and life can resume.

## 6. Conclusions and recommendations

There is a conflict between the demands of countries to return to normal production and life and the long-term nature of the COVID-19 pandemic. Using 11 institutional-social-ecological factors, this study identified six key factors associated with the case-fatality rate of COVID-19 based on the MGWR model. These factors were proven to have spatial heterogeneity in the case-fatality rate of COVID-19. And the research results proved that the results are robust. The study explained the COVID-19 severity from an SES perspective and further tested the

**Table 8**  
Statistical description of the GWR regression coefficient.

Variable	Mean	STD	Min	Median	Max
Gross domestic product (GDP)	-0.763536775	0.170274504	-0.401402575	-0.782827074	-1.083438504
Press freedom	-0.835842797	0.155197434	-0.445964868	-0.87115137	-0.985918872
COVID-19 testing policy	-0.494006522	0.11432551	-0.227143804	-0.527044695	-0.600958902
COVID-19 vaccination policy	-0.26794781	0.038001008	-0.215307744	-0.28897514	-0.301778345
Population density	0.038371257	0.008609107	0.018172753	0.037993638	0.049916725
Age dependency ratio	-0.531071757	0.158665664	-0.302272528	-0.525075988	-0.725850596
Share of the population using the Internet	-0.557264546	0.021431729	-0.527814029	-0.553281953	-0.593447966

applicability of the SES framework in a non-commons context on the basis of Ling et al. [13]. Through the SES analytical framework providing a theoretical basis, 134 countries and regions were studied to derive institutional-social-ecological factors that affect the case-fatality rate of COVID-19, according to the ascending effect size, these factors are COVID-19 vaccination policy, age dependency ratio, press freedom, gross domestic product (GDP), COVID-19 testing policy, and population density.

Although the identified SES factors are not globally significant for the case-fatality rate of COVID-19, the study can nevertheless offer recommendations for countries around the world in the context of the long-term coexistence of economic output and daily life with COVID-19. First of all, countries should try their best to popularize COVID-19 vaccinations, especially those countries and regions with undeveloped public health resources and larger dependant populations. Secondly, although the results showed that population mobility and contact will increase the case-fatality rate of COVID-19, it is difficult for most countries to implement the pandemic travel restrictions at this stage. Therefore, countries should actively increase the provision of corresponding public health facilities and funds, such as, adding more clinics in hospitals and providing medical subsidies for COVID-19 patients. Third, those countries with strong governments should implement temporarily mandated measures to restrict the media, such as legislation governing COVID-19-related news. Such a move is reasonable given that interfering with the implementation of the government's COVID-19 policy will threaten the lives and safety of others. Meanwhile, those governments that do not have the capacity should actively report the knowledge from WHO and experts through the media to improve people's awareness of COVID-19 pandemic prevention. Fourth, countries should conduct themselves with an internationalist spirit and help each other in the COVID-19 pandemic, especially helping those countries with smaller economies and poor public health resources.

The study identified the SES factors that affect the case-fatality rate at the national level through a robust method during the Omicron variant epidemic period. This is necessary, because, at this stage, the world is eager to reduce the impact of the COVID-19 pandemic to restore normal economic activity and return to daily life. However, most of the research on the severity of COVID-19 focuses on the early stage of the pandemic. With the spread of different COVID-19 variants, COVID-19 vaccine inoculation, and changes in population structures, relevant research urgently needs to be updated to provide recommendations for countries around the world to resume life and production from the impact of the pandemic. This study contributes new insights into the research methodology in relevant studies. By comparing the global ordinary least squares (OLS) model, the spatial heterogeneity of SES factors on the case-fatality rate of COVID-19 was confirmed, and the robustness of the results was tested by another local model (GWR model). In relevant global studies, the spatial heterogeneity of factors' effects has not been discussed [6,23,22]. Moreover, this study demonstrated the feasibility of applying the SES framework in the field of pandemic prevention and control. The SES framework can systematically and comprehensively identify relevant factors, which can avoid the one-sidedness of the study on COVID-19 pandemic prevention and control. Finally, there are a few relevant studies involving so many countries and regions [67,68,66,47,24], with more relevant studies

limited to specific regions, such that they cannot provide guidance for solving the pandemic at the global level. This is because the factors affecting the severity of COVID-19 are different in locations and at different times [64], and the COVID-19 pandemic has become a worldwide public health problem. Even though there are some relevant studies involving multiple countries around the world, such studies only demonstrated individual sub-systems in the social-ecological systems [6,23,22].

Based on the above, apart from the practical significance of this study suggesting several recommendations that help resolve the contradictions between the demands of countries to return to normal production and life and the ongoing, severe pandemic situations in terms of resource shortages, insufficient industrial production, social disorder, and economic loss, this study has multifaceted novelties and strengths. Firstly, the study via regression-based models showcased the theoretical application of the SES framework in the COVID-19 context. Secondly, in terms of methodology, the study innovatively considered the global spatial heterogeneity using MGWR in accurately identifying key SES factors that help explain countries' COVID-19 severity, and lastly, the study provided empirical contributions to the responses of 134 countries to the COVID-19 pandemic.

Despite the above contributions, this study has three limitations. Due to the lack of statistical related items and limited data in some countries, the study has not been able to cover all countries and regions. In addition, since the study primarily relied on one formal source of data, it cannot avoid analysis bias stemming from the statistical and reporting errors of countries. Finally, the study did not further analyze the interactions of institutional-social-ecological factors (mediating effects) in the process of affecting the case-fatality rate of COVID-19. Therefore, these limitations deserve further exploration in the future.

#### CRedit authorship contribution statement

**Xuerui Shi:** Writing – original draft, Conceptualization, Methodology, Software, Visualization. **Gabriel Hoh Teck Ling:** Conceptualization, Writing – review & editing, Validation, Supervision. **Pau Chung Leng:** Writing – review & editing. **Noradila Rusli:** Writing – review & editing. **Ak Mohd Rafiq Ak Matusin:** Writing – review & editing.

#### Declaration of Competing Interest

The authors declare no conflict of interest.

#### Data availability

Data will be made available on request.

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