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The impact of COVID-19 on economy, air pollution and income: evidence from China

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Abstract

The global pandemic caused by the outbreak of COVID-19 has posed significant risks to our health. Preventive measures such as closed management have greatly affected the economies, environments and societies of various countries. Economy, air pollution and income are three important interconnected aspects of sustainable development. However, current research lacks systematic quantitative analysis of their relationships. To fill the gap, this study adopts monthly data from January 2016 to April 2022 and constructs both a Simultaneous Equation Model (SEM) and a Time Varying Parameter Stochastic Volatility Vector Autoregressive (TVP-SV-VAR) model to empirically analyze the impact of COVID-19 on China's economy, air pollution and income. This study finds that the COVID-19 has a negative impact on China's economy and income, and a positive impact on air pollution, and the impact of the COVID-19 is systematic. In addition, there is an inverted-U shaped relationship between air pollution and economics, and a positive correlation between economic and income. The impact of COVID-19 on the economy, air pollution and income show a process of sharp fluctuations to gradual stabilization that gradually stabilized over time. This process is time-varying in the short-term, medium-term and long-term. The impacts are persistent at three different time points (before, during and after the outbreak of COVID-19), but the negative impact on the economy and income is persistent, while the positive impact on air pollution is limited. This study provides a more systematic and dynamic understanding of the COVID-19 preventive and mitigation measures in China and even the world, which helps to provide insights into the formulation of more comprehensive planning strategies in the future.

Keywords COVID-19 · Economy · Air pollution · Income · Impact · Inverted-U shaped relationship

1 Introduction

The health and survival of people around the world have been threatened and many countries have adopted containment measures since the outbreak and global spread of COVID-19. However, such measures (e.g., "stay-at-home" orders, travel restrictions, workplace closures) have also inhibited the development of global trade, consumed vast amounts of material and financial resources, and left global industries in need of innovation. Although most countries, except for China, have taken measures to "live with COVID", the ongoing outbreak of the pandemic continues to affect countries around the world, causing social unrest, ethnic tensions/conflicts and economic recession. In particular, China is going through an essential period of unprecedented change, with exceptional opportunities as well as challenges. The significant risks posed to China's development due to the outbreak of COVID-19 have greatly increased the instability of its economy and impeded income growth, but improved air pollution.

The influences of COVID-19 on many aspects of the economy, air pollution, and income have been explored by a number of studies (e.g., Kabir et al. 2020; Firano and

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Fatine 2020; Malahayati et al. 2021; Zhang et al. 2022; Wang and Su 2020; Elsaid et al. 2021; Nundy et al. 2021; Chen et al. 2021; Su et al. 2022; Sun et al. 2022; Koyama et al. 2022; Oyenubi et al. 2022). On the economic front, the outbreak of COVID-19 has caused great damage to world economic giants and national macroeconomics (Kabir et al. 2020; Firano and Fatine 2020). Many countries, especially developing countries, have been affected by the economic stagnation caused by Covid-19 shortly after the outbreak (Malahayati et al. 2021), while embargoes issued by governments have further restricted commercial activities and the movement of labor, causing continuous damage to the economy (Zhang et al. 2022). The impact of COVID-19 on the economy is characterized by phase and short-term contingency. Moving on to air quality, the levels of air pollution improved significantly shortly after the outbreak in China (Wang and Su 2020). Such improvements, along with the favorable impacts on water and wastewater quality, have been reported in a worldwide study (Elsaid et al. 2021), and the impact of the pandemic on air pollution can be extended to the impact on sustainable development goals (Nundy et al. 2021). Moreover, the relationship between air pollution and the transmission intensity and pathogenicity of the COVID-19 has also been studied (Chen et al. 2021). It is therefore important to strengthen ecological protection to prevent and control the pandemic. In terms of income, from a global perspective, the outbreak of COVID-19 has increased the disease burden and income inequality in various countries (Tetiana and Deeksha 2021; Su et al. 2022). This is predominantly caused by the increased unemployment rate in the tourism industry due to the collapse of international travel (Sun et al. 2022). The income inequality has also resulted in unequal medical treatment (Koyama et al. 2022). In addition, the above factors could worsen people's mental health, with an increased prevalence of depression and anxiety, which could further adversely affect income growth (Oyenubi et al. 2022). Moreover, the outbreak of COVID-19 has made an enormous impact on the labor market and household income in many economies (Iuliia 2022). The COVID-19 has multiple impacts on economic, environmental and energy issues (Wang and Zhang 2021, 2022b; Wang et al. 2022a; Sharif et al. 2020; Sovacool et al. 2020Wang and Wang 2020), and economy, environment and energy are also closely related (Li et al 2021; Liu et al. 2019; Ma et al. 2019; Wang et al. 2022a, 2022b).

Despite the fact that many studies have examined the mechanisms and characteristics of the impact of COVID-19 on the economy, air pollution, and income, individually, there has been limited exploration of the overall and systematic impacts of the pandemic on these three areas simultaneously. Additionally, these studies have not fully accounted for the time-varying nature and dynamic trends of the pandemic's impact. In his monograph General System Theory: Foundations, Development, Applications, introduced the concept of general system theory. He argued that integrity, relevance, dynamics and timing are fundamental characteristics of all systems, and proposed the use of the concept of integrity or system to tackle complex problems. As a global public health event, the impact of COVID-19 on us is complex and diverse. Therefore, this study systematically studied the impact of COVID-19 on the economy, air pollution and income, and further explored its dynamic shocks and time-varying characteristics. A systematic study of the impact of COVID-19 would be conducive to utilizing correct policies to stabilize the economy and society. An exploration of the different impact characteristics of COVID-19 would allow for more effective preventive measures to be taken in response to shocks in a more specific manner.

To fill the research gaps identified above, this study explores the impact of COVID-19 on China's economy, air pollution and income. Specifically, this study addresses the following questions:

1. Does the outbreak of COVID-19 have a beneficial or detrimental impact on the Chinese economy, air pollution and income?
2. Whether the impact of COVID-19 on the economy, air pollution and income is systemic?
3. Whether the impact of COVID-19 on economy, air pollution and income is time-varying?
4. What are the characteristics of the dynamic impact of COVID-19 on the economy, air pollution and income?

Addressing the above questions could be important for ensuring China's economic stability for several reasons. First, such studies are conducive to the recovery of China's economy and income growth, and beneficial to air pollution abatement, in the post-pandemic era. Besides, the studies are expected to gain insights into the adjustment of relevant pandemic prevention and control measures from a time-varying and dynamic perspective. Second, the research questions may guide China to develop pandemic prevention and preparedness measures that are in harmony with the economy, environment and people's lives in many aspects under the new development stage. Third, the questions may help us better prevent and mitigate the impact of non-systemic risks (e.g., COVID-19) associated with China's economic development.

To answer the above questions, this study analyzes the temporal evolution of economic, air pollution and income conditions in each of the provinces in China before and after the occurrence of COVID-19 based on data released for the period of 2016 to 2022. This study then constructs the simultaneous equation model (SEM) and the Time

Varying Parameter Stochastic Volatility Vector Autoregressive (TVP-SV-VAR) model together with economic, air pollution and income indicators as dummy variables to quantitatively analyze the hypothesized impact, and time-varying characteristics and dynamic shocks of COVID-19 outbreak. The research findings from this study are expected to not only address the gaps in the related literature but also provide insights for relevant stakeholders to prevent and mitigate the adverse impact of COVID-19 in China from various perspectives. Furthermore, this study may offer practical implications and theoretical values to the steady and sustainable development of China.

As a pioneer empirical study, our research contributes to the existing literature in several ways. First, it combines many aspects of the economy, air pollution and income into a single framework, and systematically explores the extent of time-varying characteristics and dynamic shocks of COVID-19 in China. Second, methodologically, advanced empirical strategies (e.g., the simultaneous equation model, the TVP-SV-VAR model) are adopted in this study to disentangle the impact of COVID-19 on China's economy, air pollution and income from multiple perspectives, therefore enhancing the external validity of the results and providing valuable references for future work.

The rest of the paper is structured as follows. Section 2 describes the data and empirical strategies. Section 3 presents the findings and answers the research questions, followed by an in-depth discussion that combines theoretical breakthroughs with policy implications. The last section concludes the paper.

2 Variables and models

2.1 Data sources

The research data of this study are primarily sourced from the official websites of the National Health Commission of China, the National Bureau of Statistics, and the China Air Quality Online Monitoring and Analysis Platform. The data on the number of new COVID-19 infections are from the National Health Commission, while Air pollution data from the China Air Quality Online Monitoring and Analysis Platform. Other data are sourced from the official website of the National Bureau of Statistics and local bureau officials. In order to compare the impact of COVID-19 before and after the outbreak, the data on the number of COVID-19 infections, GDP, AQI and per capita disposable income range from January 2016 to April 2022, while data for other variables range from January 2016 to December 2021 due to data acquisition issues.

2.2 Variable selection

The COVID-19 indicator is expressed as the logarithm of the number of new infections. The Economy indicator used in this study is the real GDP per capita with January 2016 serving as the base period. In addition, AQI is selected as an air pollution index, which is a dimensionless index to quantitatively describe air quality. The main pollutants involved in the evaluation of air quality are fine particulate matter (PM2.5), inhalable particulate matter (PM10), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3) and carbon monoxide (CO). In order to eliminate the influence of seasonal trend, the Census X-12 method was adopted to adjust the variable seasonally. The income indicator is the logarithmic of the disposable income per capita.

Finally, several control variables, i.e., the square of the logarithm of real GDP per capita, foreign direct investment, fixed capital investment, labor force, openness to the world, industrial structure, technological progress and population density, are included in the models. Foreign direct investment is converted to CNY using the average value of the exchange rate in a given month. Labor force is the number of people employed in the year. Openness to the outside world is measured by the ratio of foreign direct investment to GDP. Industrial structure is the ratio of the added value of the secondary industry to GDP. The number of invention patent applications granted is used for technological progress.

GDP, secondary industry value added and disposable income per capita are recorded as quarterly data. According to traditional econometrics methods, the data are converted into monthly data using quadratic interpolation. However, due to the availability of data, GDP per capita, fixed capital investment, labor force, technological progress and population are obtained as annual data, but transformed into monthly data using the same method. Furthermore, in line with the practice of many scholars, all variables except for AQI which is measured in percentage, are all transformed to their logarithmic forms (For detailed information regarding the descriptive statistics of the variables, please refer to Appendix Table 1 in the supplementary materials).

2.3 Model setting

In order to address the potential endogeneity issues among the proxies of economic development, air pollution levels and income, and to facilitate the study of the relationships among those elements, this study uses a simultaneous equation model (SEM) instead of a single equation model to study the impact of COVID-19 as an exogenous macroeconomic shock in China. This study therefore

follows two recent studies (Song and Yu 2020; Pornkul 2020) and proposes the following time-series Simultaneous Equation Models.

$$\ln rpgdp_t = \alpha_0 + \alpha_1 num_t + \alpha_2 AQI_t + \alpha_3 \ln Tech_t \\ + \alpha_4 \ln FDI_t + \alpha_5 Open_t + \alpha_6 \ln K_t + u_t \quad (1)$$

$$AQI_t = \beta_0 + \beta_1 num_t + \beta_2 \ln rpgdp_t \\ + \beta_3 (\ln rpgdp)^2 + \beta_4 \ln income_t + \beta_5 Pop_t \\ + \beta_6 \ln Tech_t + \beta_7 Stru_t + u_t \quad (2)$$

$$\ln income_t = \gamma_1 num_t + \gamma_2 \ln rpgdp_t + \gamma_3 AQI_t + \gamma_4 \ln L_t \\ + \gamma_5 \ln K_t + \gamma_6 Stru_t + \gamma_7 \ln Tech_t + u_t \quad (3)$$

where Eq. (1) is the economic equation, $rpgdp_t$ denotes real GDP per capita at time t, which is used to measure the level of economic development. AQI_t is the Air Quality Index at time t, reflecting the level of air pollution. num_t denotes the number of people newly infected with COVID-19, measuring the severity of COVID-19. *Tech, FDI, Open* and *K* are control variables that represent technological progress, foreign direct investment, openness to the outside world and fixed capital investment. Equation (2) is the air pollution equation, which employs the Environmental Kuznets (EKC) model to capture the nonlinearity between air pollution and economic development. In this equation, *Pop* and *Stru* represent population density and industrial structure, respectively. Equation (3) is the income equation, $income_t$ is the disposable income per capita at time t and L_t is the labor force at time t. The residual term *u* incorporates other potential influences.

A TVP-SV-VAR model is used to quantify the impact of COVID-19 on the domestic economy, air pollution and income. Primiceri (2005) estimated a Time-Varying Structural Vector Autoregression based on a Structural Vector Autoregressive model (SVAR) and proposed a TVP-SV-VAR model in which the time variation is derived from both the coefficients of the model and the variance covariance matrix. An efficient Markov Chain Monte Carlo algorithm is proposed for shift coefficients and multivariate stochastic volatility estimation, which can be evaluated numerically for the posterior of the target parameters. Nakajima (2011) optimized the calculation of the TVP-SV-VAR model, arguing that in most cases, the data generation process for economic variables has shift coefficients and shocks from stochastic fluctuations. The Markov Chain Monte Carlo (MCMC) algorithm can be used in the context of Bayesian Inference to address the problem.

A SVAR model with s-order lags is defined as:

$$Ay_t = F_1 y_{t-1} + \cdots + F_s y_{t-s} + \boldsymbol{\mu}_t, \quad t = s+1, \ldots, n \quad (4)$$

where y_t is a k × 1-dimensional observation vector. *A* is a k × k-dimensional matrix of joint coefficients. F_i is a

k × k-dimensional matrix of lagged coefficients, and the perturbation term μ_t is a k × 1-dimensional structural shock, $\mu_t \sim N(0, \sum^2)$. It is assumed that the relationship between structural shocks obeys recursive identification, i.e., the matrix *A is* a lower triangular matrix, where:

$$A = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ a_{21} & 1 & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ a_{k1} & \cdots & a_{k,k-1} & 0 \end{bmatrix},$$

$$\sum = \begin{bmatrix} \sigma_1 & 0 & \cdots & 0 \\ 0 & \sigma_2 & \cdots & 0 \\ \vdots & \vdots & \cdots & \vdots \\ 0 & \cdots & 0 & \sigma_k \end{bmatrix} \quad (5)$$

Multiplying both sides of Eq. (4) simultaneously by A^{-1} gives a simplified form of the SVAR model.

$$y_t = B_1 y_{t-1} + \cdots + B_s y_{t-s} + A^{-1} \Sigma \varepsilon_t, \varepsilon_t \sim N(0, I_k) \\ B_i = A^{-1} F_i, \quad i = 1, \ldots, s \quad X_t = I_k \otimes (y'_{t-1}, \ldots, y'_{t-s}) \quad (6)$$

where ⊗ denotes the Kronecker product, stacking the elements in B_i according to the row elements to form the column vector β. The above equation can be further expressed as:

$$y_t = X_t \beta + A^{-1} \Sigma \varepsilon_t \quad (7)$$

While all parameters are usually assumed to be invariant in SVAR models, Primiceri (2005) and Nakajima (2011) broaden the parameter invariance assumption to treat SVAR models as time-varying, i.e., the parameters are assumed to vary continuously over time and obey a time-varying first-order random walk process. Then TVP-SV-VAR model with stochastic fluctuations can be constructed as shown in Eq. (4):

$$y_t = X_t \beta_t + A_t^{-1} \Sigma_t \varepsilon_t, \ t = s+1, \ldots, n \quad (8)$$

$$\beta_{t+1} = \beta_t + \mu_{\beta t} \quad (9)$$

$$a_{t+1} = a_t + \mu_{at} \quad (10)$$

$$h_{t+1} = h_t + \mu_{ht} \quad (11)$$

$$\beta_{s+1} \sim N(\mu_{\beta 0}, \Sigma_{\beta 0}), a_{s+1} \sim N(\mu_{a0}, \Sigma_{a0}), h_{s+1} \sim N(\mu_{h0}, \Sigma_{h0}) \quad (12)$$

where the coefficients (β_t), the joint cube coefficients (A_t) and the random fluctuation covariance matrix ($\sum_t$) show time-varying characteristics.

Referring to Nakajima (2011) and other scholars, a_t is the column vector of non-zero and 1 elements of the triangular matrix A_t, i.e., $a_t = (a_{21}, a_{31}, a_{32}, \ldots, a_{k,k-1})'$, Also, let $h_t = (h_{1t}, h_{2t}, \ldots, h_{kt})'$, and $h_{it} = \log(\sigma_{it}^2), i = 1, \ldots, k; t = s+1, \ldots, n..$

2.4 Spatial and temporal evolution

The number of new infections in the COVID-19 has radiated from the central region (Hubei) to the surrounding areas, gradually evolving into a situation where the number of new infections is increasing across China (Fig. 1). Although China has taken corresponding control measures (such as health codes), the number of new infections in COVID-19 continues to increase, that is, the spread of COVID-19 virus has a continuous impact on China's economy, air pollution, income and other aspects.

COVID-19 has had an adverse impact on China's economic development, with the adverse effects being more pronounced in the Central and Western regions (Fig. 2). From 2019 to 2020, at the beginning of the outbreak of the COVID-19, only the GDP of the western region experienced changes. With the outbreak of COVID-19, China's

provinces experienced obvious changes in GDP from 2020 to 2021, particularly in the Central and Western regions.

The air quality index experienced a significant improvement after the outbreak of the COVID-19 (Fig. 3). From 2019 to 2020, the AQI index experienced a large-scale decline, especially in the Beijing-Tianjin-Hebei and central and eastern regions. From 2020 to 2021, the AQI index rose in a few provinces, but more areas still showed a marked decline compared to 2019.

The growth of disposable income per capita decelerated in general, and several provinces showed a decline in growth after the outbreak of the COVID-19 (Fig. 4). From 2019 to 2021, the average income level of residents continued to increase, but the growth rate was significantly hindered after the outbreak of the COVID-19. This is because COVID-19 has had a clear negative impact on people's incomes.
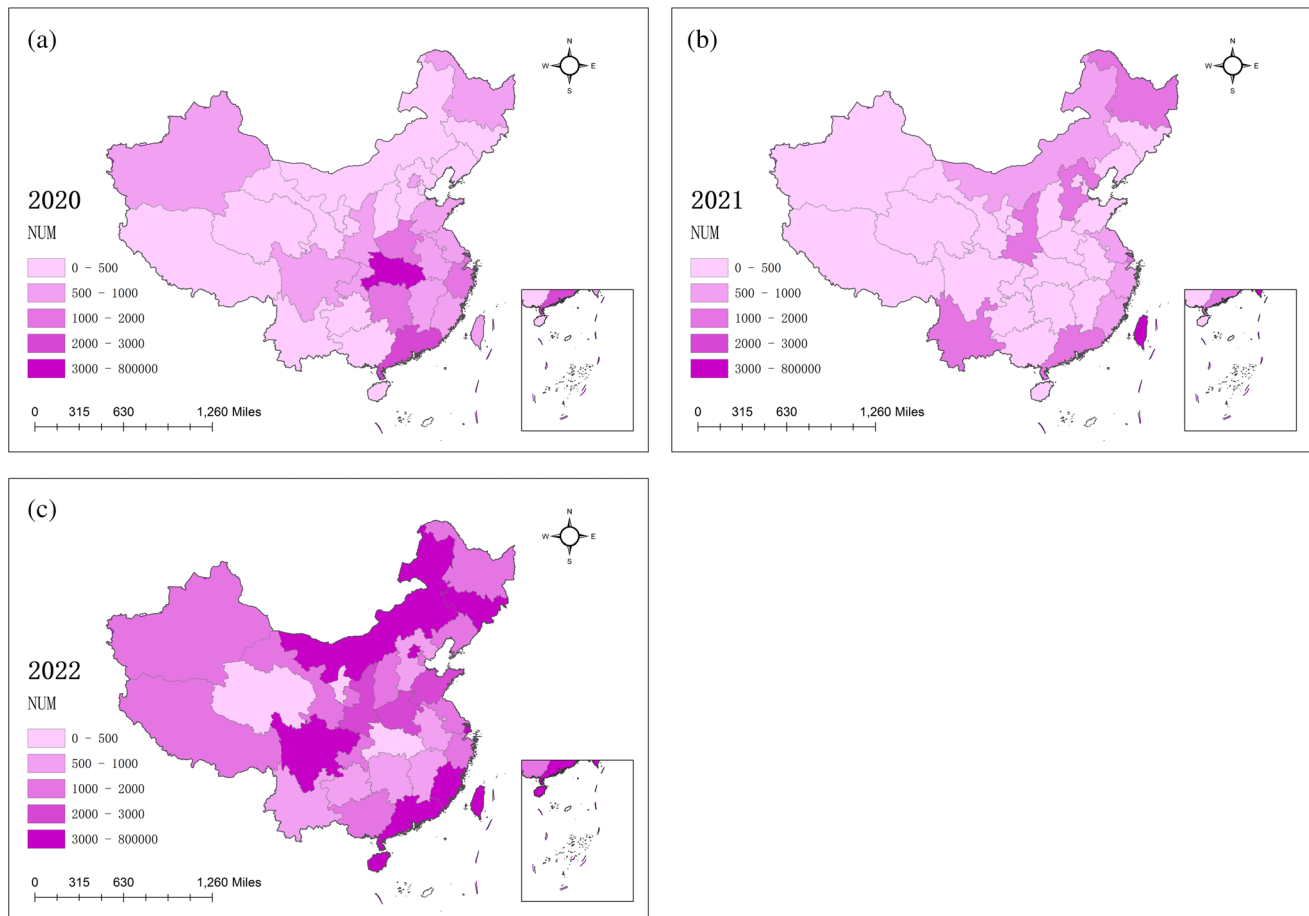

Fig. 1 Spatial and temporal evolution of the number of new infections in the COVID-19. This study used the number of new COVID-19 infections in China from January 10, 2020 to November 10, 2022, to draw a spatial and temporal evolution map. **a–c** shows the spatial and temporal evolution of the number of new COVID-19 infections in 34 provinces (autonomous regions or municipalities) in China in 2020, 2021 and 2022
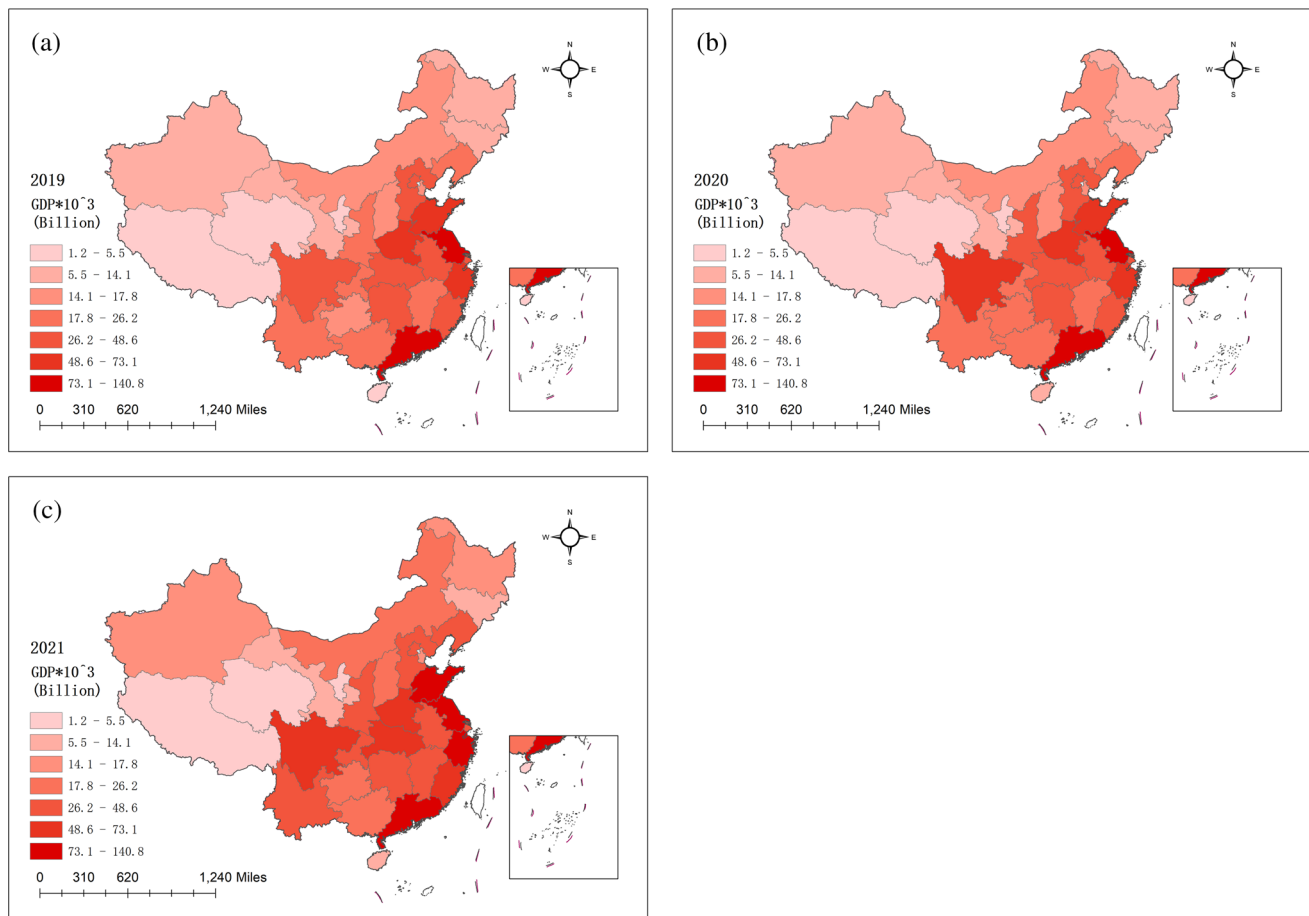
Fig. 2 Spatial and temporal evolution of GDP. **a–c** shows the spatial and temporal evolution of GDP in 31 provinces of China (excluding Hong Kong, Macao and Taiwan) from 2019 to 2021, comparing economic development in the year before and after the outbreak of COVID-19.

3 Results

3.1 The systemic impact of COVID-19 on China's economic, air pollution and income

The COVID-19 had a negative impact on China's economic development and income, while simultaneously having a positive impact on air pollution. The inherent relationship among these three factors suggests that the impact of the COVID-19 is linked and systematic (Fig. 5). There is a quadratic nonlinear relationship between economy and AQI, and a positive linear relationship between economy and income. Based on the internal relationship between economy, air pollution and income, it can be preliminarily judged that the negative impact of the epidemic on the economy will lead to the decline of income, and improve the air pollution to a certain extent. The correlation between economy and the number of new infections in the COVID-19 is significantly negative ($\alpha_1 = -0.0103$, $P < 0.01$). In addition, technological progress, opening up and fixed capital investment have a

positive impact on economic development, and there is a negative correlation between air pollution and economy. As an inverse measure of air pollution, AQI index is negatively associated with the number of new infections in the COVID-19 ($\beta_1 = -2.6271$, $P < 0.01$), revealing that the pandemic improves the air quality after the outbreak of COVID-19 in China. For the other control variables, this study notes that technological progress, income level and industrial structure are all significant determinants. Moreover, the study finds an inverted U-shaped relationship between the economy and air pollution ($\beta_2 > 0$, $\beta_3 < 0$). This implies that the AQI index initially increases with economic growth, but eventually starts decreasing as the economy continues to develop. Income levels are found to be negatively associated with the number of new infections in the COVID-19 ($\gamma_1 = -0.0238$, $P < 0.01$), whereby the outbreak of COVID-19 has reduced the disposable income per capita in China. This study also shows a negative association between air pollution and income levels, and the economy is positively correlated with income level. Finally, among the other control variables, technological
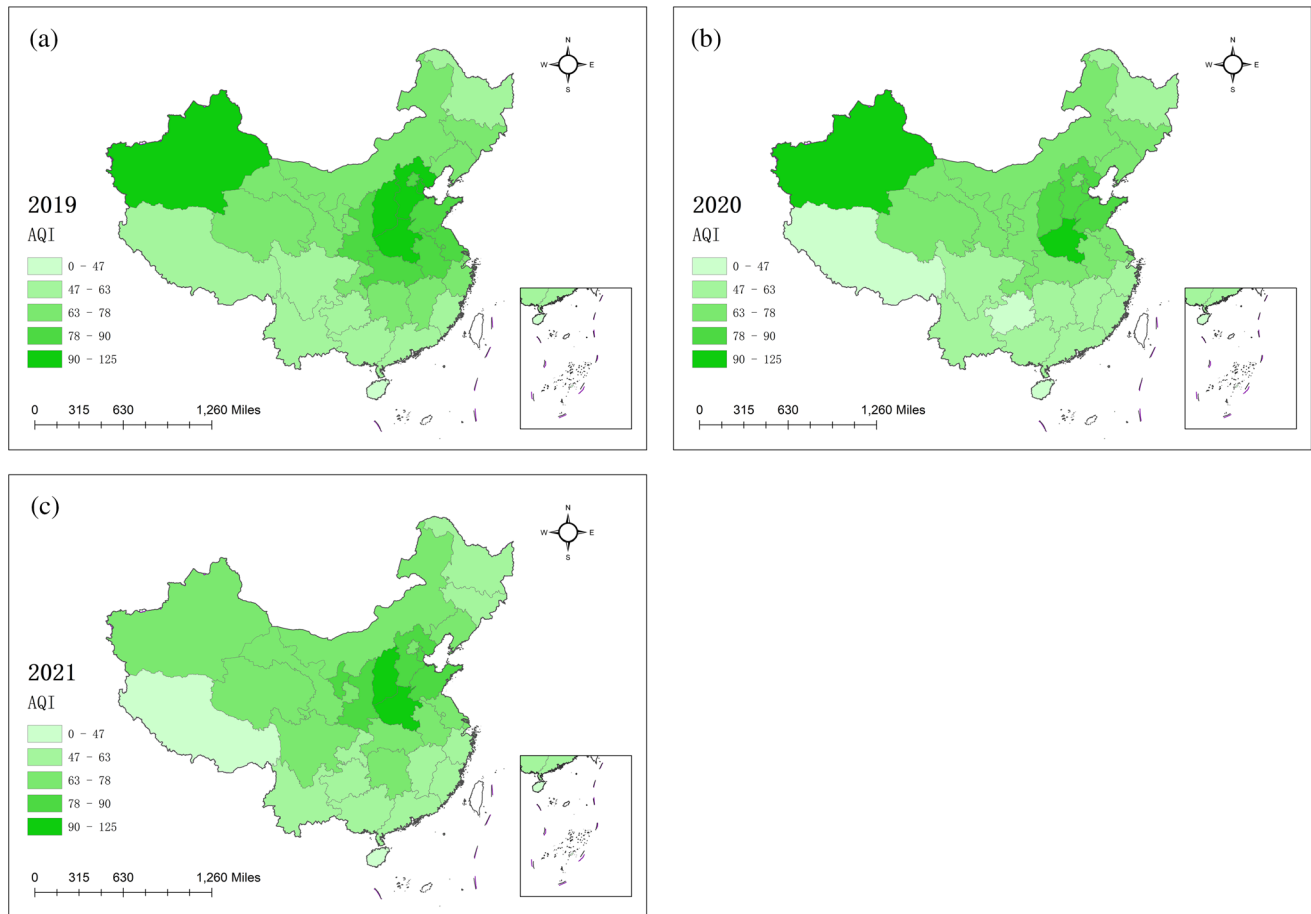
Fig. 3 Spatial and temporal evolution of AQI index. **a–c** shows the spatial and temporal evolution of AQI in 31 provinces of China (excluding Hong Kong, Macao and Taiwan) from 2019 to 2021, comparing air quality level in the year before and after the outbreak of COVID-19

progress and industrial structure are also found to be determinants of income levels. In summary, the empirical results suggest that the greater the number of new infections of COVID-19, the worse it is for the economy and income, and the better it is for reducing air pollution. The empirical results of SEM have proved the correctness of the preliminary judgment, indicating that the impact of COVID-19 on economy, air pollution and income is synergistic and systematic. Problems 1 and 2 in the introduction are solved.

3.2 Time-varying impact of COVID-19 on economic, air pollution and income

The impact of COVID-19 on China's economy, air pollution and income was a process of violent fluctuation, and had a strong time-varying characteristic (Fig. 6). The impact of COVID-19 in the short-term is large, and then shows a steady trend in the long-term, eventually increasing with period. In the medium-term, the impact of COVID-19 on the economy and income decreased significantly, but the impact on air pollution showed a clear

downward trend. The impact remained significant due to the epidemic's high level of destructiveness and continuity. The impact of the pandemic on air pollution is positive, and shows a trend from short-term sharp fluctuations to long-term gradual stability. After the COVID-19 outbreak, the impact decreased gradually over time. The impact of the outbreak on income was also a process from large fluctuation to gradual stability. The COVID-19 has a negative impact on income, and the impact shows a decreasing trend. Judging from the size of the impact of the epidemic, although the outbreak of the COVID-19 has brought some improvement in air pollution, it cannot offset its damage to the economy and income. In conclusion, the impact of the COVID-19 on the economy, air pollution and income is time-varying, showing a sharp fluctuation to gradual stabilization trend over time. Problem 3 in the introduction is solved.

The impact of COVID-19 on China's economy, air pollution and income was persistent (Fig. 6). Until April 2022, the COVID-19 still had a significant negative impact on the economy and income, with a considerable improvement in air pollution. In the early days of the
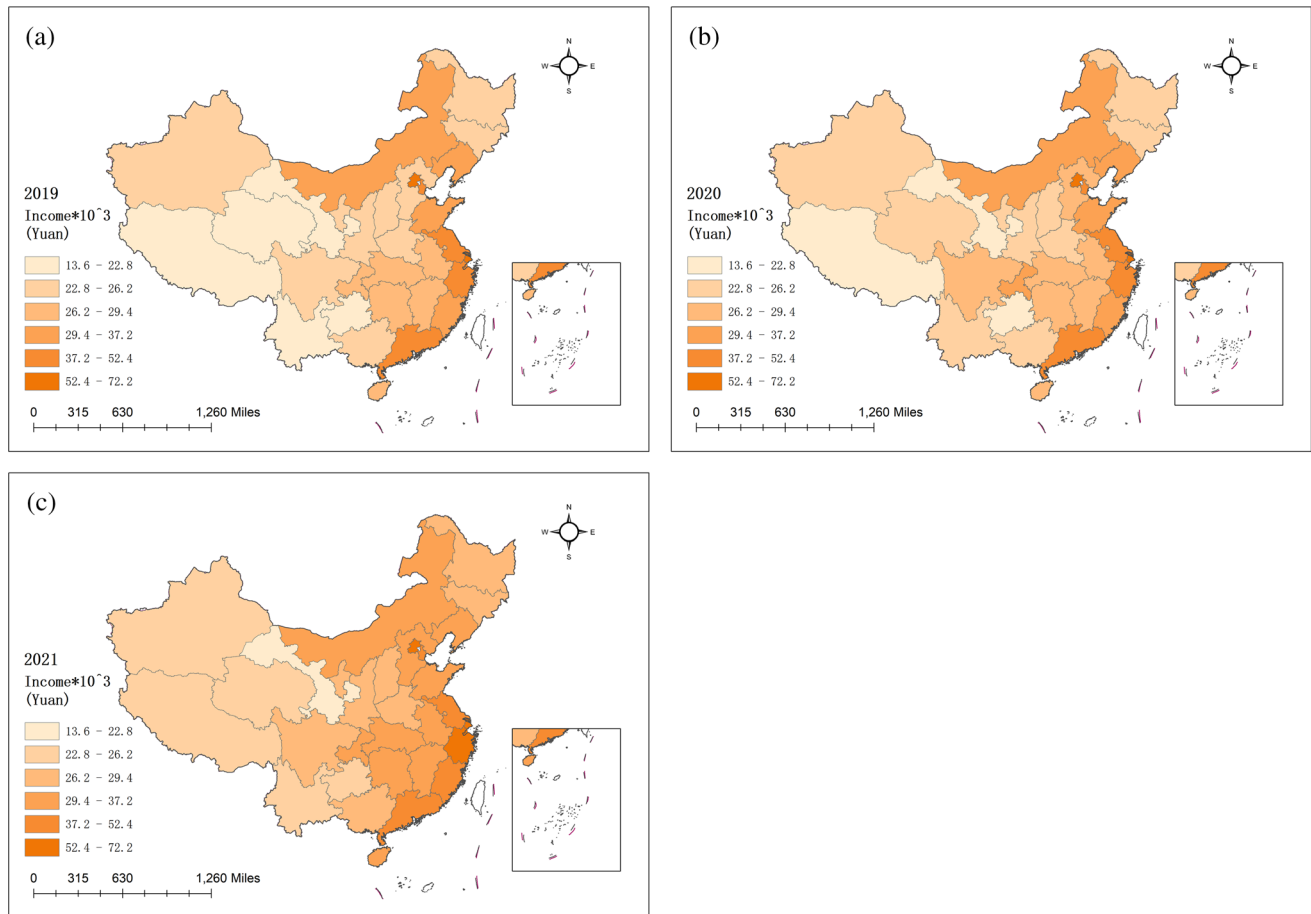
Fig. 4 Spatial and temporal evolution of disposable income per capita. **a**–**c** shows the spatial and temporal evolution of income in 31 provinces of China (excluding Hong Kong, Macao and Taiwan) from 2019 to 2021, comparing resident income level in the year before and after the outbreak of COVID-19

COVID-19 outbreak (January 2020), compared to before the pandemic (December 2017), the impact on the economy, air pollution and incomes had all been significantly reduced, indicating that the COVID-19 had a substantial impact on these factors. Two years after the outbreak of the COVID-19 (April 2022), the impact of the pandemic was even more intense. Among them, as the number of new COVID-19 infections increases, the negative impact on economy and income becomes more permanent, but the improvement effect on air pollution is limited. In addition, the impact of COVID-19 on itself is positive, resulting in the recurrence and persistence of the epidemic. By simulating the impact of COVID-19 at different points in time, it is found that it has the characteristics of continuity and stability, while its impact will be limited when it approaches a certain extent. Problems 4 in the introduction is solved.

4 Discussion

This study offers a quantitative evaluation of the impact of COVID-19 on China, taking into account the complex interplay of economic, environmental and social factors, for the first time in the literature. On the one hand, the relationship between economic development and air pollution status is characterized by an inverted-U shape, with air pollution levels increasing with economic development at the beginning and subsequently decreasing. On the other hand, the relationship between economic development and income level is positive, while air pollution status has a weak positive correlation with income level. Through the intrinsic relationship between economic development, air pollution and income level, especially the positive correlation between economic development and income level, it can be inferred that the pandemic has a similar impact on China's economy and income. At the same time, based on the "inverted U" relationship between economy and air pollution, it can be inferred that COVID-19 has an opposite
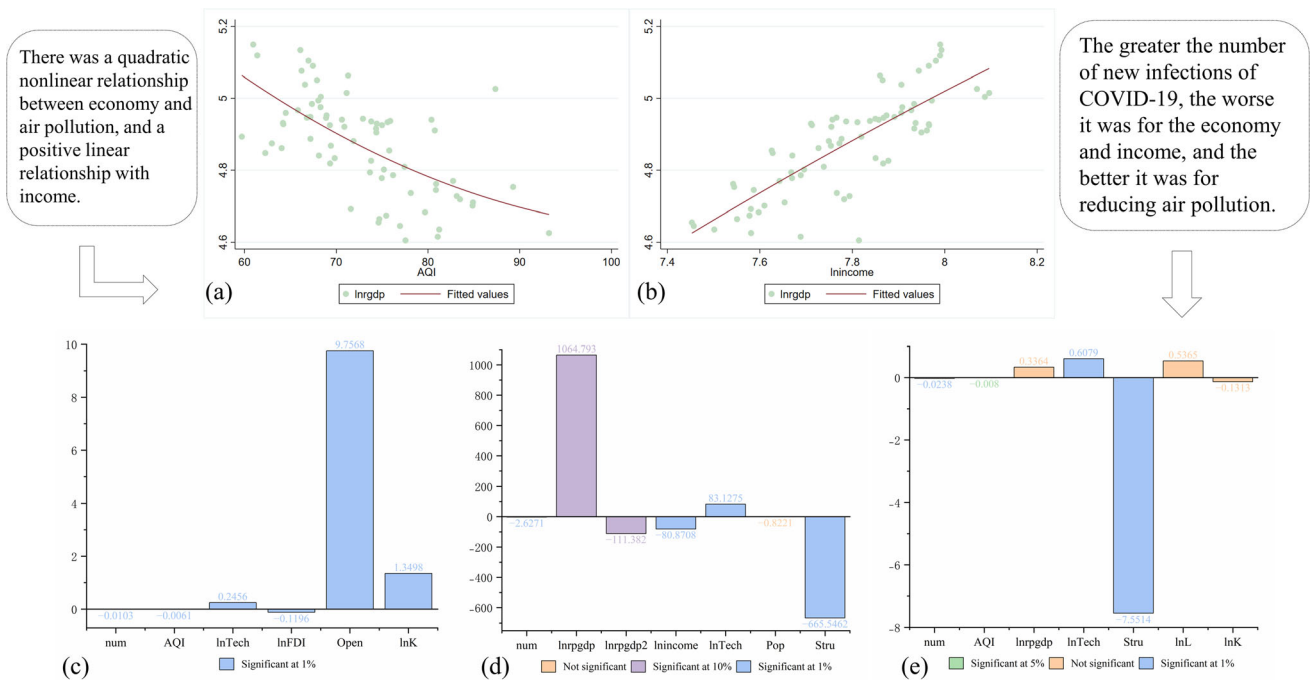
Fig. 5 The impact of COVID-19 on China's economy, air pollution and income. The relationship between GDP, AQI and income was inferred according to the scatter plot in (**a**) and (**b**), and then the impact of COVID-19 on GDP, AQI and income was demonstrated through the SEM in (**c–e**). (Please see Appendix Table 2 of supplementary materials for detailed empirical results, Including coefficient size, significance level, R^2, etc.)
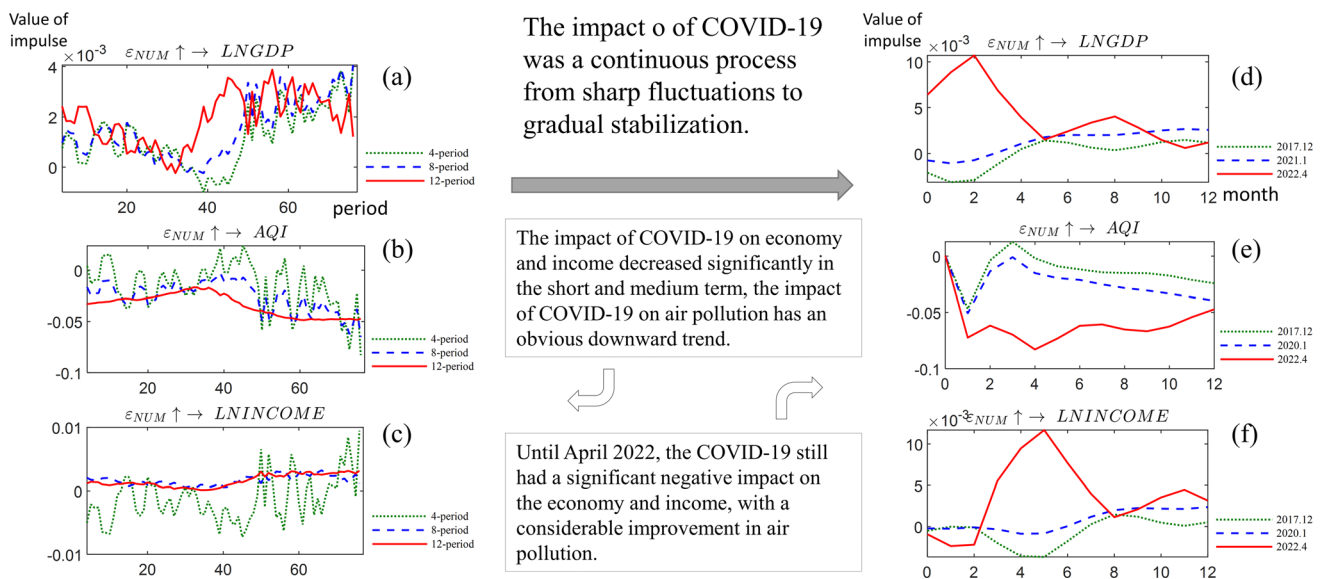

Fig. 6 Shocks to GDP, AQI and income from COVID-19 at the same time interval and different points in time. **a–c** shows the shocks of COVID-19 on GDP, AQI and income at the same time interval. The green dotted line in the legend represents the impact with a lag of 4 periods, the blue dotted line represents the impact with a lag of 8 periods, and the red solid line represents the impact with a lag of 12 periods. Shocks at the same time interval are chosen to simulate the short-, medium- and long-term effects of COVID-19. **d–f** was shocks of COVID-19 on GDP, AQI and income at different points in time. In the legend, the green dotted line represents the impact at the time point in December 2017, the blue dotted line represents the impact at the time point in January 2020, and the red solid line represents the impact at the time point in April 2022. Impacts at different time points are selected to simulate the impacts before, during and after the outbreak of COVID-19. (Please see Appendix Tables 3–6 and Appendix Fig. 1 of supplementary materials for details on the reliability and validity of the TVP-SV-VAR model)

effect on the economy and air pollution. The results of the Simultaneous Equation Model confirm the linkage of the inference, indicating that as an exogenous shock, the pandemic's impact on China is not unilateral or single, but rather linked, multivariate and multi-faceted.

This study should pay more attention to the long-term dynamic impact of COVID-19, and strive to normalize the pandemic. Despite the adverse impact of COVID-19 on China's economy in the short term, the Chinese government is able to quickly adopt some targeted policies to start recovering the economy and maintain stability. In terms of long-term economic development, it is an indication of the strength of China's economic resilience and the foresight and effectiveness of its strategies to promote high-quality economic transformation and development.

It would be better if the study formulates strategies based on different impact characteristics, and use the interplay of economy, air pollution and income to address the negative impact of the epidemic from a global perspective. The impact of the pandemic on economy, income and air pollution changes over time, indicating that the impact of the pandemic has a certain degree of permanence. It is clear that the lockdown and the reduction of industrial and human activities caused by the rapid spread of COVID-19 had a positive effect on air pollution in China, but they also caused a shock to the economy and people's income. In order to reduce the adverse impact of the epidemic, it would be beneficial for this study to focus on maintaining the improvement of air pollution caused by COVID-19 while stabilizing the economy and income. Although the economy is highly correlated with income, the impact of COVID-19 on income is more complex in the whole system. One of the possible reasons may be that in the short-term, there is a time lag, as well as the widespread of working at home, which both alleviated the negative impact caused by the pandemic.

The income of the vast majority of the population was affected in the medium-term due to the Closed Management measures adopted by the government. Nevertheless, in the long-term, China's economic development and residents' income levels begin to recover, due to the implementation of high-quality transformational development strategy, the partially adjusted industrial structure and the economic resilience of the market economy system with unique Chinese characteristics. Generally, income is highly correlated with the level of economic development, which is very important to people. However, in different periods, the leading factors of the impact of COVID-19 on income are different, which makes the impact characteristics unstable and complex.

This study explores the persistent impact of COVID-19 across different time points (before, during and after the outbreak of COVID-19). The observed dynamic characteristics and time-varying shocks can be used as a reference for countries under the background of the current global pandemic of COVID-19. Among them, the negative impact of COVID-19 on economy and income was persistent, but the improvement of air pollution was limited. With the expansion of the pandemic, the impact is also enlarging. Although many preventive measures have been taken, the impact of COVID-19 on the economy, air pollution and income cannot be ignored. The outbreak of COVID-19 resulted in widespread lockdowns and quarantines, causing significant economic losses. However the drastic reduction in population movement, industrial production and other activities also reduced carbon and sulfur emissions and other pollutants, especially air pollution, which is one of the key elements of the environment.

Considering the significant and sustained impact of COVID-19 on the economy, air pollution and income, policies promoting economic development, improving air quality and stabilizing income levels are provided from three different perspectives. For the economy development, China may wish to improve macroeconomic stability, microeconomic market efficiency and industrial structure diversification, and continue to improve the level of economic resilience, promote high-quality economic transformation and development. In addition, it may be beneficial to strengthen counter-cyclical macroeconomic control and improve the ability to prevent and resolve non-systemic financial risk in order to stabilize the economic recovery and growth conditions in the post-pandemic era. For air pollution improvement, the government may focus on strengthening efforts towards air pollution control, speeding up the construction of air pollution monitoring infrastructure, establishing sound pandemic monitoring mechanisms and early warning systems, and improving China's health emergency management. At the same time, the government could also support the development of the new energy technology industry, using technological innovation, kinetic energy conversion and other ways to continue to improve air pollution. For the income, the government should stabilize people's income expectations and the job market, further improve the social security system and the public service system for urban and rural employment, guide people to allocate their family income rationally, improve their risk resistance and risk tolerance level to stabilize the restoration of social order in the post-pandemic era, and promote the smooth implementation of subsequent pandemic prevention and control measures.

5 Conclusion

In summary, COVID-19 has a negative impact on China's economic development and income levels, and a positive impact on air pollution conditions. There is an intrinsic correlation between economic development, income levels and air pollution conditions. In addition, the impact of COVID-19 on these three elements in China may change with the development of the virus, with persistence and significance, and the impact characteristics at different points in time could be heterogeneous.

6 Theatrical implication

Based on emergent major health events, general systems theory, relevant literature and econometric models, this study discusses the impact of COVID-19 on China's economy, air pollution and income. There are few quantitative analyses of the systemic impact of COVID-19, which enriches the research in this subfield, and verified the properties of holism and correlation in general systems theory.

Specifically, this study considers the multiple impacts of the COVID-19 on the economy, environment and society from a systematic perspective, breaking through the limitation that most scholars in the past only studied the impact of a single aspect. In the face of more complex and changeable situations, this study helps to enhance the cognition of the impact of the COVID-19 and the ability to apply systematic thinking to solve problems.

7 Managerial implication

The outbreak of COVID-19 has had an impact on the world that cannot be ignored. In this context, it is of practical significance to summarize the experience and lessons and analyze the advantages and disadvantages for the recovery and development in the post-COVID-19 era, which will help restore confidence to a large number of ordinary citizens who are suffering from economic downturn, declining incomes or even unemployment. In addition, it will help the Chinese government to put in place more timely pandemic prevention and control measures, gradually improve the Macroeconomic regulation and control level of the government, the Chinese economy and income levels steadily prosperity, and gradually improve air quality.

The outbreak of COVID-19 has brought some improvement in air pollution, which should raise people's awareness of the environment and the importance of environmental pollution. In this context, human beings, as important members of the system of social development, should support economic, environmental and social recovery through their actions. In addition, this study believes that the damage of COVID-19 to the entire social development system is limited, and believes that with the responsible efforts of citizens around the world, economic, environmental and social development will be continuously promoted.

8 Limitation and future direction

This study also has some limitations due to data acquisition issues. The research time cannot be updated to the recent time, and the data scale cannot be refined to the daily degree, which need to be improved in the future.

This study provides a reference for the linkage impact of sudden public health events on the economy, environment, and society. In the future, further research can be conducted on the impact of other sudden events, and even more detailed aspects can be affected. Perhaps, multiple events can also be studied simultaneously on the relationship between economy, environment, and society.

Declarations

Conflict of interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Ethical approval This study did not involve the use of human or animal subjects.

Consent to participate This study did not involve studies of human subjects.

Consent to publish This study did not involve personal data.

Supplementary Information

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