

# Environmental Quality, Energy Consumption and Economic Inequality in China: Smooth Structural Shifts and Causal Linkages

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**Abstract** The space-temporal evolution of economic inequality is examined with Markov chain test method, and the dynamic interrelationships among environmental quality, energy consumption, and economic inequality in China from the province-level are tested by focusing on accounting for structural shifts in causal linkages in this paper. We first employ the Toda-Yamamoto causality framework and then augment it with a Fourier approximation which captures structural changes as a smooth process. The empirical findings show that taking into account smooth structural shifts is important for the causal linkages between economic inequality and energy consumption, and also between environmental quality and energy consumption. The causality analysis with structural changes provides a causal linkage between economic inequality and energy consumption in 26 out 30 provinces and a causal linkage between environmental quality and energy consumption in 7 out 30 provinces, while the quantities are 22 out 30 and 5 out 30 respectively when not accounting for structural shifts. These findings are consistent with the fact that provincial economics in China have experienced structural changes in economy-environment-energy sectors. We also conduct additional analyses which point out that regional and cyclical dependency matter for the causal relationships, and the method of HP filtering can not effectively solve the problem of smooth shifts in economy-environment-energy causality.

**Keywords** environmental quality; energy consumption; economic inequality; causal linkages; structural shifts; China

## 1 Introduction

Economic development is an evolving process, from the mid-to-late 1980s to 2007, about 20 years after the US subprime mortgage crisis broke out, and the world has experienced what some economists call ‘great stability period’<sup>[1]</sup>. Especially from 2002 to 2007, it is the ‘yellow-golden period’ of the highly optimistic view of world economic growth, and the rapid growth has become

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Received January 10, 2023, accepted July 26, 2023

Supported by R&D Program of Beijing Municipal Education Commission (SM202310038009)

a powerful engine for world economic growth of China since then. Although this process was interrupted by the international financial crisis that broke out in 2007–2008, economic growth in China has attracted worldwide attention<sup>[2]</sup>. However, with the rapid economic development, China also faced problems such as shortage of resources, excessive energy consumption, serious environmental pollution, and uneven regional development<sup>[3]</sup>.

As the largest developing country in the world, China has a vast territory and a large gap in resource endowments, and its regional development is still in an imbalanced and insufficient state<sup>[4, 5]</sup>. And the income inequality underlies many areas of inquiry in the study of regional economics and economic development in particularly<sup>[6]</sup>. Most topics of growth centers, regional dualism, pockets of poverty, and the North-South problem all deal in part with regional inequality are discussed<sup>[7]</sup>. Since 1908s an expanding literature has attempted to clarify the energy consumption and economic growth nexus<sup>[8, 9]</sup>; and environmental protection and economic growth nexus<sup>[10, 11]</sup>. More recently, the energy consumption and economic inequality development relationship has begun to attract people's attention. Among them, in the green growth and sustainable development, Yang, et al.<sup>[12]</sup> introduced ecological environment and energy utilization into the framework of economic inequality development with a one-way relationship. Some scholars believe that, a combination of globalisation and technological change has significantly improved the level of technology, and the study of the substitution relationship among economic development, environment and energy is more complicated<sup>[13, 14]</sup>.

In recent years, the increase in the share of industry and services in an economy enhances the demand for energy and new investments which necessitates more economic support that in turn trigger the development of regional economic development. Moreover, the transformation process in China's market suggests that economic markets and energy sector interact with each other and analyzing the economy and energy nexus has important implications in China from province-level. Our study differs from the previous works and contributes to the literature by providing new information to better understand the economy-environment-energy nexus. First, the two-way channels of economy, environment and energy markets are considered in this paper to dig out the mutual influence among the three, which can provide research and design basis for setting more diverse and complex relationships. Second, considering the adverse effects of non-stationary structures on bi-directional channel relationships, the smooth structural shifts are introduced to the causal framework to explore the real relations among them. Third, the Markov chain is introduced to further analyze the regional evolution of economic inequality and explain the phenomenon in combination with geographical orientation. Therefore, this study contributes to the literature by focusing on to what extent causal linkages in economy-environment-energy nexus are affected from structural changes from China's market perspective.

The remainder of this paper is organized as follows: Section 2 presents the empirical literature on the economic development, environmental quality and energy consumption nexus. Section 3 outlines the distribution characteristics of economic inequality from the aspects of measurement method and Markov chain test. Section 4 contours the economic methodology and describes the data. Section 5 discusses the results and findings, followed by Section 6 with the additional analysis. Finally, Section 7 concludes the paper.

## 2 Literature Review

During the last decade, researchers have paid increasing attention to economy-environment-energy relationships. Two main groups should be noticed, the complex relationship and influencing factors among the three.

As far as the study of the complex relationship is concerned, it mainly includes the relationship between economic inequality and environmental quality and the relationship between economic inequality and energy consumption. On the one hand, in terms of the relationship between economic inequality and environmental quality, whether the levels of environmental degradation and per capita income follow an inverted U-shaped pattern has been widely considered in the literature since the early 1990s<sup>[15]</sup>. Moreover, several researchers have attempted to empirically test the validity of this relationship, known as the environmental Kuznets curve (EKC). In addition, some scholars have calculated regional development gaps based on population-weighted coefficients and space-industry decomposition measures<sup>[16, 17]</sup>. It is believed that the imbalance of regional economic development obeys Kuznets's inverted U-shape hypothesis. Although the existing literature has conducted many empirical studies on the relationship between the two, there is still much debate. The principal argument points to econometric issues. Many authors criticize the reduced-form regression approach, which is a standard estimation method employed in the EKC empirical literature<sup>[18, 19]</sup>. Some scholars argue against inferring causality or drawing policy conclusions based on these estimates<sup>[20, 21]</sup>, because the EKC is critical to the inclusion of additional controls and the sample size and period in the results changes are very sensitive. Specifically, they show how certain assumptions about the flexibility of temporal trends influence the rejection or acceptance of proposed reduced-form relations based on subjective cognition<sup>[22, 23]</sup>. In addition, studies have shown that standard co-integration techniques commonly used in empirical EKC studies are often inappropriate<sup>[24, 25]</sup>. Therefore, the two-way relationship between economic inequality and environmental quality must be considered.

On the other hand, regarding the relationship between economic inequality and energy consumption, there is a commonly recognized argument that a high-energy of energy consumption leads to more economic and investment activities<sup>[26]</sup>. Some scholars estimate a dynamic panel data model to examine the impact of financial and economic development on energy consumption, or investigate the determinants of clean energy use by controlling financial and economic development<sup>[27, 28]</sup>. However, it has not been done on the relationship of reverse influence. In addition, in order to explain regional heterogeneity, some scholars conducted panel Granger causality analysis on three provinces in China, and realized that there may be a causal relationship between economic development and energy consumption, which is a major advance in empirical method<sup>[29]</sup>. In fact, another channel needs to be addressed in the previous studies: Energy consumption may also affect economic development through a saving channel. Unlike theoretical research, the empirical literature has not yet put forward a framework that takes the different effects of economic inequality on economic growth via the accumulation of energy and physical capital into account.

As far as the study of influencing factors is concerned, there have been observed many determinants of pollution, such as growth, industrial production, energy consumption and ur-

banization. There are various outlooks through which, the on-hand study will dictate the literature<sup>[11, 30]</sup>. In the primary constituent of the investigation, we recognize literature on the nexus between consumption of energy, economic growth and environmental pollution (CO<sub>2</sub> emission). Varied outcomes have been informed owing to the diverse features of the nations<sup>[31, 32]</sup>. Numerous investigations have empirically verified the association between growth and ecological degradation in unlike countries by engaging different econometric procedures, besides with an assorted pointer for measurement of ecological position<sup>[33, 34]</sup>. Substantial literature recorded on the nexus between consumption of energy, growth and environmental worsening integrating diverse others-controlled variables.

To sum up, the existing literature on economy-environment-energy nexus provides the ambiguous results that may stem from econometric methods, different measures of economic inequality and/or environmental quality and/or energy consumption or the sample period. However, studying such issues is crucial to consider the structural changes in the causal relationship between economic development, environmental protection, and energy consumption. Moreover, focusing on multiple comparisons from different structures of the Toda-Yamamoto causality framework and then augmenting it with a Fourier approximation is the best way to solve it with different estimation methods of generalized least squares (GLS), generalized method of moments (GMM), and seemingly unrelated regression (SUR). The above design makes an in-depth analysis of the causal relationship between the two of three, and this is also the work done in this paper.

### 3 Distribution Characteristics of Economic Inequality

#### 3.1 Measurement of Economic Inequality

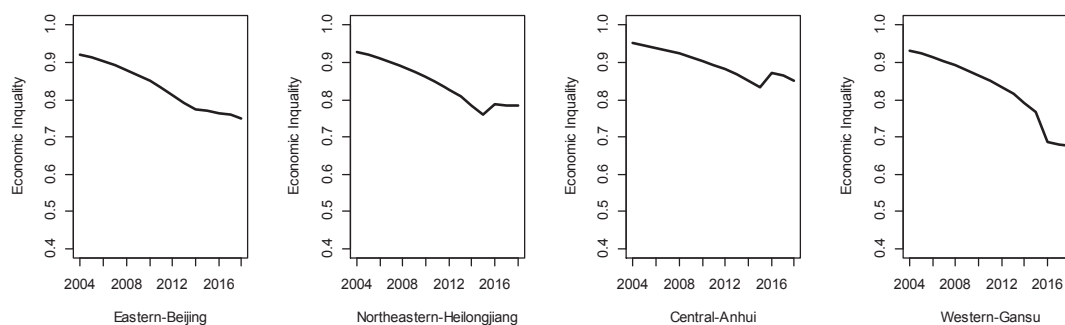
Before answering the above questions, an important task is to quantitatively analyze the degree of economic inequality. Based on the total factor production (TFP) measurement, from the perspective of high-quality economic development, Liu, et al.<sup>[35]</sup> attempted to scale the regional economic imbalance through relative comparison indicators. Therefore, the inverse absolute dispersion method is used to measure the degree of economic inequality (EI), set as

$$EI_{it} = 1 - \frac{|TFP_{it} - \frac{1}{N} \sum_{i=1}^N TFP_{it}|}{\frac{1}{N} \sum_{i=1}^N TFP_{it}}. \quad (1)$$

In Equation (1),  $i$  ( $i = 1, 2, \dots, N$ ) is the  $i$ -th province,  $t$  ( $t = 1, 2, \dots, T$ ) is the  $t$ -th period,  $EI_{it}$  represents the degree of economic inequality in  $i$ -th province at  $t$ -th period,  $TFP_{it}$  represents the total factor production in  $i$ -th province at  $t$ -th period.

Additionally, the TFP can be measured by stochastic frontier analysis (SFA), which is proposed by Aigner, et al.<sup>[36]</sup> to construct a stochastic frontier based on the production function of the input or output optimal property, and obtain the TFP by comparing the actual value of the production process with the optimal value (see Liu, et al.<sup>[35]</sup> for details). In this paper, the 'Permanent inventory method' is used to calculate the variable of capital stock by using the indicator of total fixed capital formation, and the number of employed people in each province to characterize the effective labor. In Figure 1, EI in various regions shows a decreasing trend with time goes by in general, while the decreasing trend among four major sectors shows some

differences. In particular, the decline trend in the eastern sector is relatively gentle, but the overall value of EI is small; the trend in the northeastern sector and the central sector is consistent, but it is obvious that the EI in the northeast region is smaller; contrary to the above three sectors, the degree of EI in the western sector has declined at a faster rate. And EI of the four major sectors have tended to be consistent especially in recent years.



**Figure 1** EI's change over time at the provincial level in China

### 3.2 Markov Chain Test of Economic Inequality

In line with the measurement of economic inequality (EI), if we want to understand the evolution of EI further at the province-level, Markov chain was used for analysis. According to the basic principle of Markov chain analysis<sup>[37]</sup>, three aspects such as discretization of the continuous EI, construction of transition probability matrix and analysis of evolution were conducted to dig.

#### 3.2.1 Discretization of the Continuous EI

The quality of economic imbalance in regional development (QEIRD) basically follows a chi-square distribution with a degree of freedom of 1 in the study of Liu, et al.<sup>[35]</sup> at the province-level in China, and QEIRD is divided into 4 grades. However, in the dynamics and evolution of QEIRD in various provinces, there is one sample in 2014 fell into category I only, during the sample period from 2004 to 2018. If we still use the classification result of the existing research, the deviation is larger, and it is impossible to fully present the various trend under the thought of high-quality development in economic inequality actually. Therefore,  $\chi^2(1)$ -based settings in this paper, EI is divided into three types.

Three types of EI have shown in Table 1, if the value of EI belongs to  $[0, 0.5707)$ , it is defined as I-type, which represents a state of relatively equality; if the value of EI belongs to  $[0.8684, 1)$ , it is defined as III-type, that implies a most unequal status of the economic development; if

**Table 1** Status classification of EI

classification	I-type	II-type	III-type
Value of EI	$[0, 0.5707)$	$[0.5707, 0.8684)$	$[0.8684, 1)$
Description of status	Relatively equality	Transitional phase	Relatively inequality

the value of EI is between 0.5707 and 0.8684, it is defined as II-type, which means a status of transitional phase from the most unequal to the relatively equality. In this study, three types of EI are used as the classification of EI due to two reasons. First, in order to take into account the state transition of EI has the characteristics of current state dependence, compared with the four classifications, the three are more stable. Second, the mode of three classifications can solve the problem that EI values are more imbalance in the second and third categories effectively, and provide a basis for the calculation of the state transition matrix.

### 3.2.2 Construction of Transition Probability Matrix

Let  $\{EI(t), t \in T\}$  be a random process, and  $T$  present each period in the empirical research. As a result of taking the value of EI into a finite state space  $M$ , 3 types of value of EI can be concluded. Moreover, expression of all possible results with conditional probability is given by:

$$P\{EI(t) = j | EI_{t-1} = i_{t-1}, \dots, EI_0 = i_0\} = P\{EI(t) = j | EI_{t-1} = i_{t-1}\}. \quad (2)$$

The transition probability of the state space of random variables in the Markov chain depends on the characteristics of the state in the previous period only in Equation (2), where  $j (1, 2, \dots, M)$ ,  $i_{t-1}, \dots, i_0 (1, 2, \dots, M)$  is the state space in which it is located. Under the three classifications of EI in Table 1, in status of Markov chain, the transition probability matrix of  $3 \times 3$  is attained.

In order to reduce the deviation caused by the disturbance of other factors in a single transfer, the transition probability matrix has been constructed by the sample period from 2004 to 2018 for 14 times, and weighted with the same weights to get the final matrix, written as:

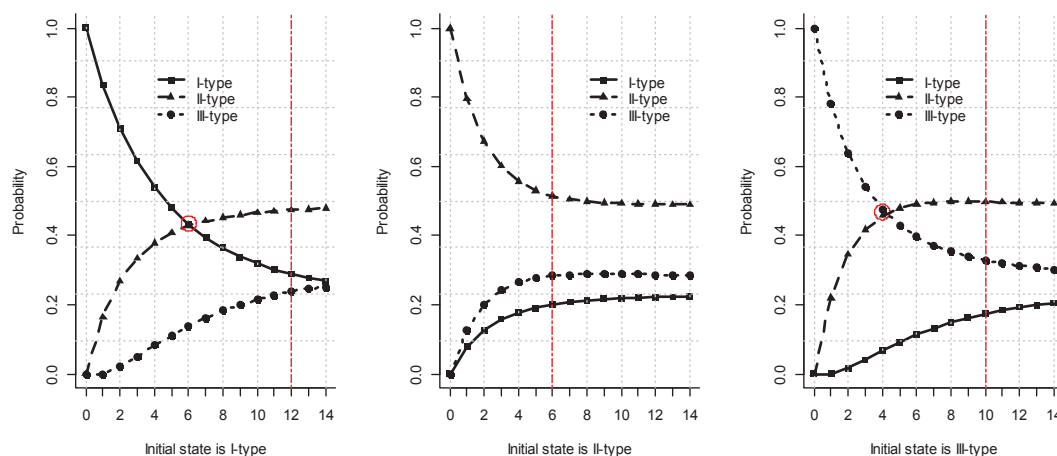
$$P_Q = \begin{bmatrix} 0.836 & 0.164 & 0.000 \\ 0.077 & 0.796 & 0.127 \\ 0.000 & 0.219 & 0.781 \end{bmatrix}. \quad (3)$$

Equation (3) can be explained: In the current period, if a region is in I-type, the probability of the region remaining in I-type at the next period is 0.836, the probability of transferring to II-type is 0.164, and the probability to III-type is 0. If a region is in II-type at this moment, the probability of the region remaining in II-type at the next moment is 0.796, the probability transfer to I-type is 0.077, and to III-type is 0.127. If a region is in III-type at this time, the probability of the region remaining in III-type at the next period is 0.781, the probability of transferring to I-type is 0, and to II-type is 0.219. Obviously,  $p_{ij} \geq 0$  ( $i, j = 1, 2, 3$ ),  $\sum_j p_{ij} = 1$  can be established. In addition, the advantage of this design is that the transition probability can be controlled in a range that does not change with time, so that the transition probability matrix has time homogeneity.

### 3.2.3 Evolution of EI

Let  $S_t$  be a row vector with  $1 \times 3$ , representing the economic inequality of China from province-level at period  $t$ , and then the state of period  $t + 1$  can be attained by the equation

of  $S_{t+1} = S_t$ . Let  $S_{10} = (1, 0, 0)$ ,  $S_{20} = (0, 1, 0)$ ,  $S_{30} = (0, 0, 1)$  be the initial state of I-type, II-type and III-type, respectively at natural. According to the setting of transition probability matrix in Equation (3), the probability of 14 times' transitions can be calculated respectively under the three different initial states.



**Figure 2** Evolution of EI from the different initial states

With the increasing of transfer's numbers, in Figure 2, the provinces with the initial state in I-type and III-type are not stable in general, and they are more inclined to shift to the II-type on the one hand; on the other hand, the provinces in II-type at initial state are more stable, and the probability of shifting to the I-type and III-type is significantly lower than maintaining the original state. More specifically, first, when a province is initially in I-type, the probability of the next period is still in the I-type is 0.836, transfer to the II-type is 0.164, and to the III-type is 0, signed as  $P_{1,1} = (0.836, 0.164, 0)$ ; and so on. After 14 times' transitions, the probability of the province is still fell into the I-type is decrease to 0.269, transfer to the II-type is increase to 0.479, which is significantly higher than that of the I-type and III-type, and transfer to the III-type is increase to 0.252, that is,  $P_{1,14} = (0.269, 0.479, 0.252)$ . Obviously, provinces in the initial state at I-type are more likely to shift to the II-type, meanwhile, the uneven development of high-quality economy has shown a stage characteristic with time goes by, especially after experiencing the 12th transfer, this probability becomes greater.

Second, when a province is initially in II-type, the probability of the next period is still in the II-type is 0.796, transfer to the I-type is 0.077, and to the III-type is 0.127, signed as  $P_{2,1} = (0.077, 0.796, 0.127)$ ; the probability of transferring to I-type is 0.077, which is slightly lower than the III-type (0.127), and so on. After 14 times' transitions, the probability of the province is still fell into the II-type is decrease to 0.49, while the probability I-type and III-type are 0.225 and 0.285 separately, that is  $P_{2,14} = (0.225, 0.490, 0.285)$ . In another words, provinces in II-type are more likely to remain in the II-type, and they are more stable in terms of transition. From the aspect of four major sectors, more provinces in central sectors are belong to II-type, they are in the transitional stage between inequality and relative inequality.

Third, when a province is initially in the III-type, the probability of the next period is still in the III-type is 0.78, transfer to the II-type is 0.22 and to the I-type is 0, signed as

$P_{3,1} = (0, 0.22, 0.78)$ . After 14 times' transitions so on, the probability of the province is still falling into the III-type is decrease to 0.302, while the probability increase to 0.494 in the II-type and 0.204 in the I-type, that is  $P_{3,14} = (0.204, 0.494, 0.302)$ . In a summary, most of the provinces in western sector belong to the III-type, and more likely to move to the II-type with a high probability, it is means that some provinces in China with a slowly development have improved their economic development level continuously, which has led to a slowing of economic inequality in recent years.

## 4 Methodology and Data Description

### 4.1 Granger Causality and Smooth Structural Shifts

The standard Granger causality analysis necessitates testing for unit root and co-integration because Wald test not only has a non-standard distribution if the variables in VAR model are integrated or cointegrated, but also depends on nuisance parameters. Toda and Yamamoto<sup>[38]</sup> have improved Granger causality overcomes these problems by estimating VAR( $p + d$ ) model by using level data where  $d$  is the maximum integration order of variables. To construct the Toda-Yamamoto causality analysis, we define VAR( $p + d$ ) system as:

$$y_t = a_0 + a_1 y_{t-1} + a_2 y_{t-2} + \cdots + a_{p+d} y_{t-(p+d)} + \epsilon_t. \quad (4)$$

where  $y_t$  consists of endogenous variables,  $a_0$  is a vector of intercept terms,  $a_1, a_2, \dots, a_{p+d}$  are coefficient matrices,  $p$  is the lag order,  $d$  is the maximum integration order of variables and  $\epsilon_t$  are the white-noise residuals. By augmenting the Toda-Yamamoto framework with a Fourier approximation, a simple approach to account for structural breaks (both abrupt and gradual) in causality analysis proposed by Nazlioglu, et al.<sup>[39]</sup> and developed by Durusu-Ciftci, et al.<sup>[40]</sup>. They relax the assumption that the intercept terms  $a_0$  are constant over time and define as  $a(t)$ , the gradual structural shifts with an unknown time, number and forms of breaks are captured by the Fourier approximation defined as:

$$a(t) \cong c_0 + \sum_{k=1}^K \kappa_{1k} \sin\left(\frac{2\pi tk}{T}\right) + \sum_{k=1}^K \kappa_{2k} \cos\left(\frac{2\pi tk}{T}\right), \quad (5)$$

where  $a(t)$  are time dependent and present structural shifts in  $y_t$ ,  $K$  is the number of frequencies,  $\kappa_{1k}$  and  $\kappa_{2k}$  can calculate the amplitude and displacement of the frequency, separately. By taking Equation (5) into Equation (4), the Toda-Yamamoto framework with a Fourier approximation can be obtained:

$$y_t = c_0 + \sum_{k=1}^K \kappa_{1k} \sin\left(\frac{2\pi tk}{T}\right) + \sum_{k=1}^K \kappa_{2k} \cos\left(\frac{2\pi tk}{T}\right) + a_1 y_{t-1} + a_2 y_{t-2} + \cdots + a_{p+d} y_{t-(p+d)} + \epsilon_t. \quad (6)$$

In this paper, we employ environmental quality (EQ), energy consumption (EC), and economic inequality (EI) as endogenous variables from the panel data and Equation (6) can explicitly be re-written as follows:

$$EI_{i,t} = c_{1,0} + \sum_{k=1}^K \kappa_{1,1,k} \sin\left(\frac{2\pi tk}{T}\right) + \sum_{k=1}^K \kappa_{1,2,k} \cos\left(\frac{2\pi tk}{T}\right)$$



$$+ \sum_{j=1}^{p+d} \alpha_{1j}^* EI_{i,t-j} + \sum_{j=1}^{p+d} \beta_{1j}^* EQ_{i,t-j} + \sum_{j=1}^{p+d} \gamma_{1j}^* EC_{i,t-j} + \epsilon_{1i,t}, \quad (7)$$

$$\begin{aligned} EQ_{i,t} = & c_{2,0} + \sum_{k=1}^K \kappa_{2,1,k} \sin\left(\frac{2\pi tk}{T}\right) + \sum_{k=1}^K \kappa_{2,2,k} \cos\left(\frac{2\pi tk}{T}\right) \\ & + \sum_{j=1}^{p+d} \alpha_{2j}^* EI_{i,t-j} + \sum_{j=1}^{p+d} \beta_{2j}^* EQ_{i,t-j} + \sum_{j=1}^{p+d} \gamma_{2j}^* EC_{i,t-j} + \epsilon_{2i,t}, \end{aligned} \quad (8)$$

$$\begin{aligned} EC_{i,t} = & c_{3,0} + \sum_{k=1}^K \kappa_{3,1,k} \sin\left(\frac{2\pi tk}{T}\right) + \sum_{k=1}^K \kappa_{3,2,k} \cos\left(\frac{2\pi tk}{T}\right) \\ & + \sum_{j=1}^{p+d} \alpha_{3j}^* EI_{i,t-j} + \sum_{j=1}^{p+d} \beta_{3j}^* EQ_{i,t-j} + \sum_{j=1}^{p+d} \gamma_{3j}^* EC_{i,t-j} + \epsilon_{3i,t}, \end{aligned} \quad (9)$$

where  $i$  ( $i = 1, 2, \dots, N$ ) is the  $i$ -th province,  $t$  ( $t = 1, 2, \dots, T$ ) is the  $t$ -th period. In the Toda-Yamamoto framework, the null hypothesis  $H_0$  of Granger non-causality is based on zero restrictions on the first  $p$  parameters and Wald statistic for this hypothesis has an asymptotic Chi-square distribution with  $p$  degrees of freedom  $\chi^2(p)$ . However, it is important to note that Wald statistic may not follow an asymptotic Chi-square distribution because it may depend on the number of frequency,  $k$ . In order to avoid this problem, the bootstrap distribution of Wald statistic by employing residual sampling bootstrap approach has been proposed by Efron<sup>[40]</sup>, and in recent works in the Granger causality literature have also relied on bootstrap distributions to increase the power of the tests in small samples, as well as being robust to the unit root and co-integration properties of the data<sup>[41, 42]</sup>. Therefore, we obtain Wald statistic from bootstrap distribution in this paper.

The most important problem in Equations (7), (8) and (9) is that determining the number of cumulative Fourier frequency  $K$  and lag lengths  $p$ . In order to determine the optimal number of lags in a causality analysis in common is to benefit from Akaike information criterion (AIC). As the recent works in the Granger causality literature shown, AIC can also be used for determining the number of Fourier frequency  $K$  and lag lengths  $p$  in this paper.

## 4.2 Data Description and Sources

Recently, various academics emerged the idea of tripartite (EEE); environment, energy, and economy, those are counted as active pillars for sustainable development of any economy<sup>[32]</sup>. We use annual data from 2004 to 2018 for 30 provinces in China, excluding Hong Kong, Macao, Taiwan, and Tibet<sup>1</sup>. Environmental quality (EQ) is measured by the proportion of days of air quality equal to or above grade II in the whole year (%), and it is derived from the indicator the days of air quality equal to or above grade II (day); Energy consumption (EC) is measured by total energy consumption per capita (tce), and can be obtained from total energy consumption ( $10^4$  tce) divide by population at year-end by region (10,000 persons). Economic inequality

<sup>1</sup>Due to the serious lack of data, we do not conduct an empirical analysis of Hong Kong, Macao, Taiwan, and Tibet in China.

(EI) is measured by Equation (1), after calculating data such as capital stock, labor, economic development level (GDP) and other indicators. All variables are in natural logarithms and all data are obtained from China Statistics Yearbook of Environment, China Energy Statistics Yearbook, China Population and Employment Statistics Yearbook, and China Statistics Yearbook from the province-level.

In this paper, proportion of days of air quality equal to or above grade II in the whole year is used as a proxy for environmental quality due to two reasons. On the one side, the quality of air reflects the degree of air pollution by minoring  $PM_{2.5}$ ,  $PM_{10}$  and other indicators in China<sup>[43]</sup>, in order to find ways to improve environmental quality, and days of air quality equal to or above grade II can intuitively and exactly reflect this phenomenon. On the other side, compared with  $PM_{2.5}$ ,  $PM_{10}$  and other indicators, the indicator data of days of air quality equal to or above grade II is more available and covers a wider range during the sample period.

Total energy consumption per capita is used as a proxy for energy consumption due to three reasons. First, energy consumption per capita considers the regional influence differences of population factors on energy distribution<sup>[44]</sup>, which can effectively reflect the average energy consumption of each province. Second, energy consumption per capita is an important indicator of a country's or region's economic development and people's living standards. Third, compared with  $CO_2$ , power consumption, water consumption and other indicators<sup>[45]</sup>, the change in energy consumption per capita is closely related to the industrialization process, and it can also systematically describe the development state of the economy.

## 5 Results and Discussions

### 5.1 Basic Parameters in Toda-Yamamoto Framework

Considering the length and value characteristics of the data in this study, we take the Fourier frequency  $K$  values from 1 to 10 respectively, use the bootstrap distribution of Wald statistic by employing residual sampling bootstrap approach to fit the sample multiple times, and use the Akaike information criterion (AIC) and mean squared error (MSE) to determine the optimal value of  $K$ . The final test results show that  $K_{\max} = 2$ .

Afterwards, the number of lag lengths  $p$  needs to define. As we all know, a common method to determine the optimal number of lags in a causality analysis is to benefit from Akaike or Schwarz information criterion, and the augmented dickeye fuller (ADF) test for variables in the panel regression to determine the order of lag. In this study, we use the ADF and AIC, according to the madwu<sup>[46]</sup> principle, through the iterative method to choice the lag lengths  $p$  and the maximum integration order of variables  $d$ . In Table 2, the values are the Chi-square statistics, the optimal lag lengths of economic inequality (EI) is 1, the optimal lag lengths of environment quality (EQ) is 2, and optimal lag lengths of energy consumption (EC) is 1 according to the AIC minimum criterion. In addition, the maximum integration order of variables is 1 by using the same criterion.

**Table 2 Summary for the direction of lag lengths**

Lag orders	$d$	$p(\text{EI})$	$p(\text{EQ})$	$p(\text{EC})$
60	105.86	17.014	95.495	1.353
1	112	28.036	103.171	2.354
2	112	26.972	113.312	2.282
3	112	27.183	94.881	1.469
Maximum order	1	1	2	1

Note:  $p(\text{EI})$  presents the lag lengths of economic inequality,  $p(\text{EQ})$  presents the lag lengths of environmental quality,  $p(\text{EC})$  presents the lag lengths of energy consumption. “Madwu” is the inverse Chi-squared test and also called  $P$  test.

## 5.2 Results from Panel Data

According to the determined values of Fourier frequency  $K$ , the lag lengths  $p$ , and the maximum integration order of variables  $d$ , we redefine Equations (7), (8) and (9), and perform parameters estimation and causality test. In this paper, the traditional Toda-Yamamoto causality framework is used as the basic model, and smooth structural shifts introduced with a Fourier approximation are used to compare the advantages of the research methods adjusted in this study.

Table 3 presents the results for Toda-Yamamoto causality between EI and EQ, EI and EC, EQ and EC. GLS, GMM and SUR methods have used to estimate the parameters of Equations (7), (8) and (9) without the Fourier approximation, respectively, in order to understand the relationship between EI, EQ, EC more comprehensively. As far as the estimation method is concerned, it is obvious that SUR method has more advantages, whether it is from the perspective of model fitting effect or the result of parameter test of causality. We can explain it from two aspects: On the one hand, the parameters that pass the significance test between EI and EQ, EI and EC, EQ and EC are significantly increased; on the other hand, compared with GMM and GLS methods, the overall fitness of the models under SUR is slightly excellent higher and more explanatory.

From the results for Toda-Yamamoto causality between EI and EQ, under the method of GLS and SUR, there is no significant Toda-Yamamoto causality between EI and EQ; while the unidirectional influence of EI on EQ is significant with the method of GMM, and it is reflected by the first-order lag negative suppression and third-order lag positive promotion coefficients<sup>2</sup>. In a summary, in the Toda-Yamamoto causality test that does not consider Fourier approximation, the causality relationship between EI and EQ has not been found.

From the results for Toda-Yamamoto causality between EI and EC, first, a significant one-way influence relationship from EI to EC existed with the method of GLS, and the coefficient of 1.31 appears as a third-order lag positive effect. Second, contrary to the GLS estimation results, there is a one-way influence relationship from EC to EI under the GMM method, and it is a second-order negative effect ( $-0.025$ ). Third, under the method of SUR, there is a two-

<sup>2</sup>The first-order lag negative coefficient is  $-23.13$ , is much larger than the third-order lag positive coefficient (0.671), therefore, with the increase of economic inequality, environmental quality will be greatly reduced.

way impact relationship between EC to EI, on the one hand, the third-order positive impact is mainly from EI to EC; on the other hand, the second-order negative impact is mainly from EC to EI. In a summary, without considering Fourier approximation in Toda-Yamamoto causality framework, a phenomenon of mutual causation between EI and EC persisted, and it is shown that the increase of EI will continue to increase EC, and the further increase of EC will reduce the level of EI, showing a certain nonlinear relationship.

**Table 3 Results for Toda-Yamamoto causality**

Variables	GLS			GMM			SUR		
	EI	EQ	EC	EI	EQ	EC	EI	EQ	EC
Intercept	0.020 (0.013)	25.273*** (6.070)	-0.512*** (0.100)	0.070 (0.283)	-15.69 (19.82)	0.116 (0.351)	0.010*** (0.003)	18.66*** (3.764)	-0.32*** (0.053)
EI <sub>1</sub>	1.425*** (0.053)	-6.783 (25.860)	-0.021 (0.427)	-0.479 (0.951)	-23.13** (8.672)	-0.946 (0.688)	1.431*** (0.012)	-3.57 (3.845)	-0.060 (0.093)
EI <sub>2</sub>	-0.500*** (0.090)	16.937 (43.530)	-0.896 (0.718)	1.418 (1.162)	-32.22 (21.28)	0.387 (0.725)	-0.493*** (0.022)	5.292 (3.189)	-0.920*** (0.181)
EI <sub>3</sub>	0.064 (0.057)	-19.78 (27.510)	1.310** (0.454)	0.000 (0.000)	0.671*** (0.054)	0.000 (0.002)	0.053*** (0.015)	-6.880 (4.139)	1.250*** (0.152)
EQ <sub>1</sub>	0.000 (0.000)	0.724*** (0.053)	-0.001 (0.001)	0.000 (0.000)	-0.121* (0.061)	0.000 (0.002)	0.000 (0.000)	0.744*** (0.019)	-0.001*** (0.000)
EQ <sub>2</sub>	0.000 (0.000)	-0.071 (0.065)	0.000 (0.001)	0.000 (0.001)	0.186 (0.116)	0.002 (0.003)	0.000 (0.000)	-0.070*** (0.016)	0.000 (0.000)
EQ <sub>3</sub>	0.000 (0.000)	0.135* (0.054)	0.002** (0.001)	0.030*** (0.007)	-0.033 (3.993)	1.042*** (0.070)	0.000*** (0.000)	0.152*** (0.012)	0.001*** (0.000)
EC <sub>1</sub>	0.007 (0.007)	16.820*** (3.395)	1.375*** (0.056)	0.010 (0.008)	0.341 (2.921)	-0.051 (0.079)	0.005*** (0.000)	7.095*** (1.434)	1.375*** (0.018)
EC <sub>2</sub>	-0.011 (0.011)	-12.390* (5.178)	-0.197* (0.085)	-0.025** (0.008)	-1.245 (3.133)	0.225* (0.106)	-0.009*** (0.001)	-6.630*** (1.301)	-0.190*** (0.024)
EC <sub>3</sub>	0.004 (0.007)	-4.190 (3.248)	-0.192*** (0.054)	0.000* (0.000)	-0.002 (0.007)	0.000 (0.000)	0.003*** (0.000)	-0.390 (1.085)	-0.210*** (0.018)
R <sup>2</sup>	0.963	0.613	0.958	0.441	0.472	0.382	0.967	0.604	0.857

Note: GLS is the parameter estimation method, which named as Generalized Least Squares; GMM is Generalized Method of Moments; SUR is Seemingly Unrelated Regression. Standard errors are shown in brackets. EI<sub>1</sub> is the first-order lag of economic inequality, EI<sub>2</sub> is the second-order lag of economic inequality, EI<sub>3</sub> is the third-order lag of economic inequality; EQ<sub>1</sub> is the first-order lag of environmental quality, EQ<sub>2</sub> is the second-order lag of environmental quality, EQ<sub>3</sub> is the third-order lag of environmental quality; EC<sub>1</sub> is the first-order lag of energy consumption, EC<sub>2</sub> is the second-order lag of energy consumption, EC<sub>3</sub> is the third-order lag of energy consumption. “\*” is the significance of 5%, “\*\*\*” represents 1%, “\*\*\*\*” represents 0.1%.

From the results of Toda-Yamamoto causality between EQ and EC, although both GLS and SUR show that there is a two-way causal relationship between EQ and EC, it is clear that this mutual causal relationship is more stable under the SUR estimation method. On the one side, EC has a first-order lag positive effect on EQ, as well as a second-order lag negative effect, which shows that the effect of EC on EQ is more complicated; It has both the third-order lag positive effect and the same complex influence relationship from EQ to EC on the other side. In summary, for the further analysis of the mutual causality between EQ and EC needs to be conducted from the direction of influence and the intensity of influence, which is also the focus of subsequent research in this paper.

Table 4 presents the results for Toda-Yamamoto causality with Fourier approximation between EI and EQ, EI and EC, EQ and EC. Considering that the difference between the estimation results of GLS and GMM under the Toda-Yamamoto causality framework is very small, this section only shows the estimation results of GLS and SUR.

From the results for Toda-Yamamoto causality with Fourier approximation between EI and EQ, although under the GLS method, there is still no significant mutual causality between EI and EQ, but their smooth structural coefficients are significant, which shows that the proposed method has certain rationality. As far as SUR method is concerned, a two-way causal relationship existed between EI and EQ, the first-order lag ( $-10.760$ ) presented from EI to EQ, while the first-order lag ( $1.242$ ), second-order lag ( $-0.006$ ), and third-order lag ( $-0.216$ ) appeared from EQ to EI. This shows that the increase of EI will cause the EC level to drop significantly, and the increase of the EC level will increase the gap of EI, which has both a restrictive effect and a promoting effect between EI and EQ.

Similarly, there is no significant mutual causality between EI and EC, but their smooth structural coefficients are significant from the results for Toda-Yamamoto causality with Fourier approximation between EI and EC. Moreover, under the method of SUR, a two-way causal relationship appeared between EI and EC, as a second-order lag ( $-0.716$ ) and a third-order lag ( $0.648$ ) existed from EI to EC; the first-order ( $0.006$ ), second-order ( $-0.008$ ), and third-order lag ( $0.003$ ) presented from EC to EI also. We can explain this phenomenon like this: On the one hand, the continuous expansion of EI will reduce EC in the short term, but it will increase EC in the long run; on the other hand, the further increase of EC will affect the EI after promoting first and suppress then, and re-promoting last, it exhibits certain fluctuations.

The difference is that under the GLS method, EC has an unidirectional first-order lag positive effect ( $8.622$ ) and a third-order negative effect ( $-6.077$ ) to EQ from the results for Toda-Yamamoto causality with Fourier approximation between EQ and EC. As far as the results of the SUR method are concerned, EQ has a first-order lag negative effect ( $-0.001$ ) and a second-order lag positive effect coefficient ( $0.001$ ) on EC; relatively, EC has a first-order lag positive driving effect ( $2.804$ ), also has a second-order negative suppressing effect ( $-2.995$ ) on EQ. In other words, EC and EQ are not only causal to each other, but also have the characteristics of long-term and short-term differences.

In summary, the study of the causal linkages between variables depends not only on whether Fourier approximation is used to shift the data smoothly in the Toda-Yamamoto causality framework, but also on the choice of estimation method. From the results in Table 3 and Table

**Table 4 Results for Toda-Yamamoto causality with Fourier approximation**

Variables	GLS			SUR		
	EI	EQ	EC	EI	EQ	EC
Intercept	0.005 (0.018)	21.810** (7.774)	-0.139 (0.126)	-0.006 (0.003)	15.410*** (4.388)	-0.080 (0.052)
$\sin(\frac{2\pi t}{T})$	0.001 (0.003)	3.407** (1.081)	-0.016 (0.017)	0.001*** (0.000)	3.369*** (0.525)	-0.012 (0.008)
$\sin(\frac{4\pi t}{T})$	-0.001 (0.002)	-6.120*** (1.043)	-0.132 (0.017)	-0.001** (0.000)	-5.302*** (0.597)	-0.107*** (0.011)
$\cos(\frac{2\pi t}{T})$	0.004 (0.003)	-0.362 (1.185)	-0.129*** (0.019)	0.004*** (0.001)	-0.673 (0.689)	-0.105*** (0.015)
$\cos(\frac{4\pi t}{T})$	0.000 (0.002)	2.947*** (0.804)	-0.057*** (0.013)	0.001** (0.000)	2.754*** (0.529)	-0.050*** (0.007)
EI <sub>1</sub>	1.417*** (0.054)	-23.590 (23.134)	0.073 (0.374)	1.422*** (0.010)	-10.760* (4.437)	0.099 (0.103)
EI <sub>2</sub>	-0.494*** (0.090)	24.037 (38.749)	-0.754 (0.626)	-0.485*** (0.019)	8.288 (5.027)	-0.716*** (0.217)
EI <sub>3</sub>	0.074 (0.058)	-12.786 (24.859)	0.738 (0.402)	0.064*** (0.012)	-3.791 (6.392)	0.648*** (0.166)
EQ <sub>1</sub>	0.000 (0.000)	0.570*** (0.052)	-0.002 (0.001)	0.000 (0.000)	0.614*** (0.021)	-0.001*** (0.000)
EQ <sub>2</sub>	0.000 (0.000)	-0.001 (0.061)	0.002 (0.001)	0.000 (0.000)	-0.015 (0.018)	0.001*** (0.000)
EQ <sub>3</sub>	0.000 (0.000)	0.279*** (0.054)	0.000 (0.001)	0.000* (0.000)	0.261*** (0.018)	0.000 (0.000)
EC <sub>1</sub>	0.008 (0.008)	8.622** (3.258)	1.242*** (0.053)	0.006*** (0.001)	2.804** (1.016)	1.250*** (0.019)
EC <sub>2</sub>	-0.011 (0.011)	-2.664 (4.787)	-0.060 (0.077)	-0.008*** (0.001)	-2.995** (1.065)	-0.071** (0.024)
EC <sub>3</sub>	0.003 (0.007)	-6.077* (2.951)	-0.216*** (0.048)	0.003*** (0.000)	-0.020 (1.236)	-0.213*** (0.016)
R <sup>2</sup>	0.968	0.705	0.964	0.976	0.698	0.942

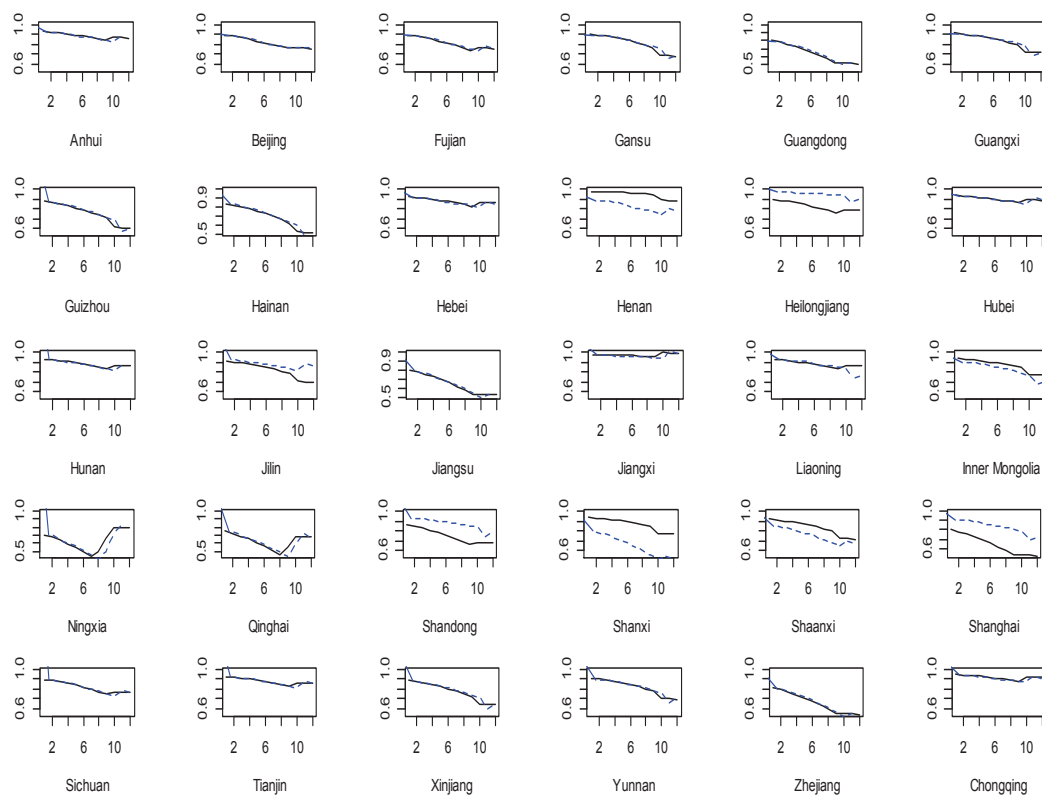
Note: GLS is the parameter estimation method, which named as Generalized Least Squares; SUR is Seemingly Unrelated Regression. Standard errors are shown in brackets. EI<sub>1</sub> is the first-order lag of economic inequality, EI<sub>2</sub> is the second-order lag of economic inequality, EI<sub>3</sub> is the third-order lag of economic inequality; EQ<sub>1</sub> is the first-order lag of environmental quality, EQ<sub>2</sub> is the second-order lag of environmental quality, EQ<sub>3</sub> is the third-order lag of environmental quality; EC<sub>1</sub> is the first-order lag of energy consumption, EC<sub>2</sub> is the second-order lag of energy consumption, EC<sub>3</sub> is the third-order lag of energy consumption. “\*” is the significance of 5%, “\*\*” represents 1%, “\*\*\*” represents 0.1%.

4, it is not difficult to see that the model which considered Fourier approximation is more in line with the current status of EI, EQ, and EC causality linkages; meanwhile, the SUR method is more universal due to its relaxation of the assumption about the correlation of perturbation terms, and we use SUR in subsequent studies.

### 5.3 Results from Province Level

The inverse absolute dispersion method is compared the degree of economic inequality, the proportion of days of air quality equal to or above grade II in the whole year and total energy consumption per capita with their Fourier approximations, respectively. It is clear that the behaviors of these variables are often province specific and dynamic trend overtime. Moreover, the province-level economies in China have experienced structural shifts among economic inequality, environmental quality and energy consumption. The functional forms of these shifts is unknown in common and there is also no priori knowledge on selecting exact break times and the number of breaks. As observed from the results, the causality framework of Toda-Yamamoto, which augmented by a Fourier approximations can capture the long wings in the series, therefore, they seem to be more accurate to control the unknown nature of the breaks in causality analysis.

Specifically, take regional economic inequality (EI) as an example for illustration. In Figure 3, EI with Fourier approximations have illustrated from province-level in China which



Note: the solid black lines show the true value of economic inequality, and the blue dotted lines are the fitting curve with Fourier approximations of economic inequality.

**Figure 3** Economic inequality with Fourier approximations

has measured by the inverse absolute dispersion method. In general, the value of EI in various provinces from 2004 to 2018 showed a slow downward trend basically, however, the range of this change showed a more obvious regional difference. We can summarize this difference from the classification characteristics of the four major sectors in China's regional economic layout. Provinces with large EI values and rapid declines are mostly located in the western regions, such as Gansu, Guangxi, and Guizhou; provinces with relatively small EI values and relatively gentle changes are mainly in the eastern and northeastern regions, such as Heilongjiang, Beijing, and Hebei; the central region is in the middle of a sharp decline and gradual changes.

Meanwhile, the EQ values of various provinces in China have a wave-shaped change trend during the sample period, and compared with the wave change of EQ and the almost linear change trend of EI, the change characteristics of EC are among the two, and the overall trend of EC is decreasing. The Toda-Yamamoto Granger causality analysis can divide into two steps, the first step is to investigate the unit root properties of the variables to determine the maximum order of integration ( $d$ ) in the VAR system, which can be reviewed in Table 2. In the second step, the results from the Toda-Yamamoto (TY) and Fourier Toda-Yamamoto (FTY) causality analyses from province-level under the method of SUR are reported in Table 5, Table 6, and Table 7. Before proceeding to inferences for causality analysis, it needs to emphasize, we test for the significance of Fourier terms in all the estimated VAR models by using an  $F$ -test. The null hypothesis of the absence of Fourier terms is rejected in most cases, implying the significance of smooth structural transitions.

Table 5 presents the results for causality between EI and EQ under the SUR method. The Toda-Yamamoto test indicates bidirectional causal relationships between EI and EQ in Guangxi and Liaoning, while the influence relationship between EI and EQ in the other 28 provinces is not significant. However, when structural breaks are taken into account, causality relations are detected for a larger set of countries. According to the Fourier Toda-Yamamoto testing procedure, along with Guangxi and Liaoning, bidirectional causal relationships between EI and EQ is also found in Guangdong and Ningxia. For these four provinces, EI is the cause of EQ, meanwhile, EQ is also the cause of EI. For the central region, there is no causality in any direction between EI and EQ.

Table 6 presents the results for causality between EI and EC under the SUR method. There is no causality in any direction between EI and EC in 8 provinces, such as Beijing, Hebei, Shanghai, Tianjin, Liaoning, Ningxia and Yunnan under the Toda-Yamamoto test framework. And for the remaining 22 provinces, there are bidirectional causal relationships between EI and EC. The results also indicate the importance of taking into account structural breaks. Apart from Beijing, Jiangxi, Ningxia and Yunnan, the bidirectional causal relationships between EI and EC exist for the remaining 26 provinces, supporting for the feedback hypothesis. Taking Fujian as an example, the intensity of the bidirectional causal relationships between EI and EC is analyzed. Under the analysis of FTY framework, EI positively acts on EC with a coefficient of 8.96, and EC slightly causes EI with an effect of 10.5. Overall, the mutual influence between the two is significant, and the difference in action intensity is small.

Table 7 presents the results for causality between EQ and EC under the SUR method. The Toda-Yamamoto test indicates unidirectional causality from EC to EQ for Ningxia. Bidirectional



**Table 5 Results for causality between EI and EQ**

Region	Province	$H_0$ : EQ does cause EI				$H_0$ : EQ does cause EI				Relation	
		TY		FTY		TY		FTY		TY	FTY
		Cof.	S.E.	Cof.	S.E.	Cof.	S.E.	Cof.	S.E.	Arrow	Arrow
Eastern	Beijing	N	—	N	—	N	—	N	—	N	N
	Fujian	N	—	N	—	N	—	N	—	N	N
	Guangdong	N	—	0.002*	0.000	N	—	1.47*	0.628	N	↔
	Hainan	N	—	N	—	N	—	N	—	N	N
	Hebei	N	—	N	—	N	—	N	—	N	N
	Jiangsu	N	—	N	—	N	—	N	—	N	N
	Shandong	N	—	N	—	N	—	N	—	N	N
	Shanghai	N	—	N	—	N	—	N	—	N	N
	Tianjin	N	—	N	—	N	—	N	—	N	N
North-eastern	Heilongjiang	N	—	N	—	N	—	N	—	N	N
	Jilin	N	—	N	—	N	—	N	—	N	N
	Liaoning	0.002*	0.000	0.001*	0.000	2.13*	0.863	2.11*	0.763	↔	↔
Central	Anhui	N	—	N	—	N	—	N	—	N	N
	Henan	N	—	N	—	N	—	N	—	N	N
	Hubei	N	—	N	—	N	—	N	—	N	N
	Hunan	N	—	N	—	N	—	N	—	N	N
	Jiangxi	N	—	N	—	N	—	N	—	N	N
	Shanxi	N	—	N	—	N	—	N	—	N	N
Western	Gansu	N	—	N	—	N	—	N	—	N	N
	Guangxi	0.012*	0.003	0.006*	0.003	1.33*	0.736	0.933*	0.436	↔	↔
	Guizhou	N	—	N	—	N	—	N	—	N	N
	Inner Mongolia	N	—	N	—	N	—	N	—	N	N
	Ningxia	N	—	0.005*	0.002	N	—	0.795*	0.361	N	↔
	Qinghai	N	—	N	—	N	—	N	—	N	N
	Shannxi	N	—	N	—	N	—	N	—	N	N
	Sichuan	N	—	N	—	N	—	N	—	N	N
	Xinjiang	N	—	N	—	N	—	N	—	N	N
	Yunnan	N	—	N	—	N	—	N	—	N	N
	Chongqing	N	—	N	—	N	—	N	—	N	N

Notes: TY: The TY approach which does not account for structural breaks. FTY: The Fourier TY approach with cumulative frequencies is based on Equation (7). N: There have not causality between EI and EQ. ↔: There is a mutual influence between EI and EQ. →: EQ does cause EI. ←: EI does cause EQ. Cof.: Coefficient of parameter estimation under SUR method. S.E.: Standard Error of the coefficient. “\*” is the significance of 5%, “\*\*” represents 1%, “\*\*\*” represents 0.1%.

Table 6 Results for causality between EI and EC

Region	Province	$H_0$ : EC does cause EI				$H_0$ : EI does cause EC				Relation	
		TY		FTY		TY		FTY		TY	FTY
		Cof.	S.E.	Cof.	S.E.	Cof.	S.E.	Cof.	S.E.	Arrow	Arrow
Eastern	Beijing	N	—	N	—	N	—	N	—	N	N
	Fujian	0.09***	0.011	0.09***	0.010	8.96***	1.06	10.5**	1.131	↔	↔
	Guangdong	0.29***	0.058	0.23***	0.024	2.31***	0.463	3.99***	0.413	↔	↔
	Hainan	0.03***	0.018	0.27***	0.033	3.21***	0.189	3.24***	0.392	↔	↔
	Hebei	N	—	0.04**	0.009	N	—	0.18**	0.048	N	↔
	Jiangsu	0.15***	0.019	0.13***	0.011	5.54***	0.719	7.29***	0.601	↔	↔
	Shandong	0.09*	0.027	0.09***	0.013	5.23**	1.502	9.47***	1.372	↔	↔
	Shanghai	N	—	0.22***	0.038	N	—	3.66***	0.646	N	↔
	Tianjin	N	—	0.04**	0.011	N	—	5.16***	0.412	N	↔
North-eastern	Zhejiang	0.19***	0.026	0.16***	0.015	4.19***	0.563	5.92***	0.591	↔	↔
	Heilongjiang	0.08**	0.022	0.08***	0.013	8.23***	1.118	10.6***	1.817	↔	↔
	Jilin	0.12**	0.031	0.17***	0.025	4.64**	1.817	5.12	0.751	↔	↔
Central	Liaoning	N	—	0.03**	0.008	N	—	2.09**	0.512	N	↔
	Anhui	0.07***	0.017	0.08**	0.018	8.36**	1.916	8.87**	1.998	↔	↔
	Henan	0.09***	0.014	0.08**	0.020	8.23***	1.118	8.13***	1.986	↔	↔
	Hubei	0.03*	0.013	0.04**	0.009	10.3*	4.377	17.3**	4.737	↔	↔
	Hunan	0.06*	0.020	0.04**	0.012	6.99*	2.351	14.6*	3.831	↔	↔
	Jiangxi	N	—	N	—	N	—	N	—	N	N
Western	Shanxi	0.09***	0.014	0.07***	0.01	8.20***	1.241	12.5***	1.917	↔	↔
	Gansu	0.09***	0.011	0.17***	0.024	5.29***	0.138	5.16***	0.639	↔	↔
	Guangxi	0.019***	0.011	0.17***	0.024	4.99***	0.278	5.01***	0.704	↔	↔
	Guizhou	0.019***	0.010	0.17***	0.021	5.04***	0.271	5.16***	0.638	↔	↔
	Inner Mongolia	0.04***	0.005	0.03**	0.008	2.01***	0.214	2.17**	0.508	↔	↔
	Ningxia	N	—	N	—	N	—	N	—	N	N
	Qinghai	0.04*	0.014	0.03*	0.012	9.82*	3.885	14.3*	5.935	↔	↔
	Shannxi	0.12***	0.012	0.11***	0.016	7.81***	0.794	8.10***	1.343	↔	↔
	Sichuan	0.009**	0.024	0.10***	0.014	5.91**	1.633	8.59***	1.332	↔	↔
	Xinjiang	0.005***	0.006	0.06***	0.006	15.9***	1.862	15.7***	1.716	↔	↔
	Yunnan	N	—	N	—	N	—	N	—	N	N
	Chongqing	0.03*	0.011	0.02*	0.008	13.5*	4.778	18.1*	8.241	↔	↔

Notes: TY: The TY approach which does not account for structural breaks. FTY: The Fourier TY approach with cumulative frequencies is based on Equation (8). N: There have not causality between EI and EC. ↔: There is a mutual influence between EC and EI. →: EC does cause EI. ←: EI does cause EC. Cof.: Coefficient of parameter estimation under SUR method. S.E.: Standard Error of the coefficient. “\*” is the significance of 5%, “\*\*” represents 1%, “\*\*\*” represents 0.1%.

**Table 7 Results for causality between EQ and EC**

Region	Province	$H_0$ : EQ does cause EC				$H_0$ : EC does cause EQ				Relation	
		TY		FTY		TY		FTY		TY	FTY
		Cof.	S.E.	Cof.	S.E.	Cof.	S.E.	Cof.	S.E.	Arrow	Arrow
Eastern	Beijing	N	—	N	—	N	—	N	—	N	N
	Fujian	N	—	N	—	N	—	N	—	N	N
	Guangdong	N	—	0.01*	0.003	N	—	5.05*	1.792	N	↔
	Hainan	0.03**	0.009	0.03*	0.012	0.15**	0.045	0.14*	0.057	↔	↔
	Hebei	N	—	N	—	N	—	N	—	N	N
	Jiangsu	N	—	N	—	N	—	N	—	N	N
	Shandong	N	—	N	—	N	—	N	—	N	N
	Shanghai	N	—	0.01*	0.003	N	—	2.34*	1.031	N	↔
	Tianjin	0.03*	0.012	0.01*	0.003	1.16*	0.492	2.64*	1.121	↔	↔
North-eastern	Zhejiang	N	—	N	—	N	—	N	—	N	N
	Heilongjiang	N	—	N	—	N	—	N	—	N	N
	Jilin	N	—	N	—	N	—	N	—	N	N
Central	Liaoning	N	—	N	—	N	—	N	—	N	N
	Anhui	N	—	0.01***	0.001	N	—	N	—	N	→
	Henan	0.005*	0.002	N	—	0.77**	0.294	N	—	→	N
	Hubei	N	—	N	—	N	—	N	—	N	N
	Hunan	N	—	N	—	N	—	N	—	N	N
	Jiangxi	N	—	N	—	N	—	N	—	N	N
Western	Shanxi	0.01*	0.004	0.02*	0.005	2.92*	1.015	3.11*	1.258	↔	↔
	Gansu	N	—	N	—	N	—	N	—	N	N
	Guangxi	0.012*	0.003	0.014*	0.006	0.44**	0.119	0.313*	0.128	↔	↔
	Guizhou	N	—	N	—	N	—	N	—	N	N
	Inner Mongolia	N	—	N	—	N	—	N	—	N	N
	Ningxia	0.014***	0.002	0.15**	0.035	N	—	N	—	←	N
	Qinghai	N	—	N	—	N	—	N	—	N	N
	Shannxi	N	—	N	—	N	—	N	—	N	N
	Sichuan	N	—	N	—	N	—	N	—	N	N
	Xinjiang	N	—	N	—	N	—	N	—	N	N
	Yunnan	N	—	N	—	N	—	N	—	N	N
	Chongqing	N	—	N	—	N	—	N	—	N	N

Notes: TY: The TY approach which does not account for structural breaks. FTY: The Fourier TY approach with cumulative frequencies is based on Equation (9). N: There have not causality between EQ and EC. ↔: There is a mutual influence between EQ and EC. →: EQ does cause EC. ←: EC does cause EQ. Cof.: Coefficient of parameter estimation under SUR method. S.E.: Standard Error of the coefficient. “\*” is the significance of 5%, “\*\*” represents 1%, “\*\*\*” represents 0.1%.

links are found in Hainan, Tianjin, Henan, Shanxi and Guangxi, meanwhile, in the remaining 24 countries, the neutrality hypothesis is hold since there is no causality in any direction. The results from the Fourier Toda-Yamamoto test show unidirectional or bidirectional links for 7 provinces and the findings for 23 provinces unidirectional causality. The null hypothesis of non-causality from EQ to EC (EC to EQ) cannot be rejected for Guangdong, Hainan, Shanghai, Tianjin, Shanxi, Guangxi and Anhui (Guangdong, Hainan, Shanghai, Tianjin, Shanxi and Guangxi). In the case of Hainan under the FTY, EQ positively acts on EC with a coefficient of 0.03, and EC causes EQ with an effect of 0.14. In comparison, although the bidirectional links between EQ and EC is significant, the effect of EC on EQ is stronger than EQ on EC in total.

As noted earlier, the above results are based on the multivariate VAR model estimations in which EI, EQ, and EC are the endogenous variables. We next discuss to what extent the causal relationships among the variables are sensitive to VAR model specifications. We thereby estimate the bivariate VAR models. This robustness analysis may be important because an omission of one variable may crucially change the empirical findings for economy-environment-energy nexus.

It needs to emphasize that the findings from the multivariate models and the bivariate models in Table 8 has been summarized by us. And “ $\rightarrow$ ” or “ $\leftarrow$ ” denotes one-way direction of causality and “ $\leftrightarrow$ ” denotes two-way direction of causality has been followed notation to simplify the presentation of findings. In Table 8, with respect to the causal links between EI and EQ, and between EQ and EC, the estimating VAR models in a multivariate or a bivariate framework considerably various the findings has appeared. It may imply that the causal relationships between these variables are sensitive to omission of the third variable on the one hand. On the other hand, when environmental quality is used as a control variable in economic inequality and energy consumption nexus affects not only the number of cases in which causality is found but also the direction of causation.

In summary, we can get the findings that (i) accounting for structural shifts has a very important effect on economic inequality & environmental quality, economic inequality & energy consumption and environmental quality & energy consumption relations; and (ii) the causal linkages are mostly sensitive to structural shifts with Fourier approximations in the economic inequality & environmental quality and environmental quality & energy consumption nexus. Therefore, policy implications may differ in light of the causality analysis with or without structural shifts.

## 6 Additional Analysis

According to the previous findings and discussions, there are two further analysis to better understand the causal linkages among them. First, regional economic development is an important feature in economic inequality development analysis<sup>[6]</sup>, due to the countries are more integrated in an open economy macroeconomics context<sup>[47, 48]</sup> and the provinces are more closely linked in China since the reform and opening up in 1978<sup>[49]</sup>.

Groenewold, et al.<sup>[50]</sup> examined the spillovers from the costal, central and western regions by the VAR model during 1953–2003, they find that three are strong spillovers from the costal region to both other regions, but the shocks to the western region have no flow-on effect on

**Table 8 Summary for the direction of causality from multivariate and bivariate models**

Region	Province	Multivariate models						Bivariate models					
		EI-EQ		EI-EC		EQ-EC		EI-EQ		EI-EC		EQ-EC	
		TY	FTY	TY	FTY	TY	FTY	TY	FTY	TY	FTY	TY	FTY
Eastern	Beijing	—	—	—	—	—	—	—	—	—	—	—	—
	Fujian	—	—	↔	↔	—	—	—	—	↔	↔	—	—
	Guangdong	—	↔	↔	↔	—	↔	—	←	↔	↔	→	↔
	Hainan	—	—	↔	↔	↔	↔	—	—	←	↔	↔	↔
	Hebei	—	—	—	↔	—	—	—	—	—	←	—	—
	Jiangsu	—	—	↔	↔	—	—	—	—	→	↔	—	—
	Shandong	—	—	↔	↔	—	—	—	—	↔	↔	—	—
	Shanghai	—	—	—	↔	—	↔	—	←	—	←	—	↔
	Tianjin	—	—	—	↔	↔	↔	—	—	—	↔	↔	↔
	Zhejiang	—	—	↔	↔	—	—	—	→	→	↔	→	—
North-eastern	Heilongjiang	—	—	↔	↔	—	—	—	—	—	—	—	←
	Jilin	—	—	↔	↔	—	—	—	—	←	↔	—	—
	Liaoning	↔	↔	—	↔	—	—	→	↔	—	—	—	—
Central	Anhui	—	—	↔	↔	—	→	—	—	—	↔	—	→
	Henan	—	—	↔	↔	↔	—	—	—	←	↔	←	—
	Hubei	—	—	↔	↔	—	—	—	—	↔	↔	←	—
	Hunan	—	—	↔	↔	—	—	—	—	—	↔	—	—
	Jiangxi	—	—	—	—	—	—	—	—	—	—	—	—
	Shanxi	—	—	↔	↔	↔	↔	—	—	↔	↔	↔	↔
Western	Gansu	—	—	↔	↔	—	—	—	—	←	↔	—	—
	Guangxi	↔	↔	↔	↔	↔	↔	→	↔	↔	↔	↔	↔
	Guizhou	—	—	↔	↔	—	—	—	—	↔	↔	—	—
	Inner Mongolia	—	—	↔	↔	—	—	—	—	↔	↔	—	←
	Ningxia	—	↔	—	—	←	—	←	↔	—	—	—	—
	Qinghai	—	—	↔	↔	—	—	—	—	←	↔	←	—
	Shannxi	—	—	↔	↔	—	—	—	—	↔	←	—	—
	Sichuan	—	—	↔	↔	—	—	—	—	↔	↔	—	—
	Xinjiang	—	—	↔	↔	—	—	—	—	—	↔	—	—
	Yunnan	—	—	—	—	—	—	—	—	—	→	—	—
	Chongqing	—	—	↔	↔	—	—	—	—	—	←	—	→

the other two regions. Li, et al.<sup>[51]</sup> studied the spatial correlation and explanation of regional economic from the four major sections by the QAP method, they found that the provinces in first section, that is, in the eastern region, have a large spillover effect on each other. Based

on their research, to further analyze the causal relationships between EI & EQ, EI & EC, and EQ & EC, we take the four major sections into account from eastern, northeastern, central and western regions.

We can draw the following findings from Table 8, that (i) compared with EI & EQ, the two-way causal linkages between EQ and EC, EI and EC is more significant; (ii) the existence of the causal relationships between EI, EQ and EC is reflected in eastern region and western region, while there is no obvious causal linkages between EQ and EC in the northeastern region, and no obvious causal relationship between EI and EQ in the central region; (iii) the causal relationships are mostly sensitive to structural shifts with Fourier approximations in the eastern region and western region, the formulation of differentiated regional economic development policies is imperative.

Another analysis is to consider the trend decomposition of periodic fluctuations. Hodrick and Prescott<sup>[52]</sup> believed that economic variables are neither constant nor random, and thought their trends to change slowly, and a method in light with symmetric data moving average is called HP filtering. We can define it as:

$$EI_{it} = G_{it}^I + C_{it}^I, \quad (10)$$

$$EQ_{it} = G_{it}^Q + C_{it}^Q, \quad (11)$$

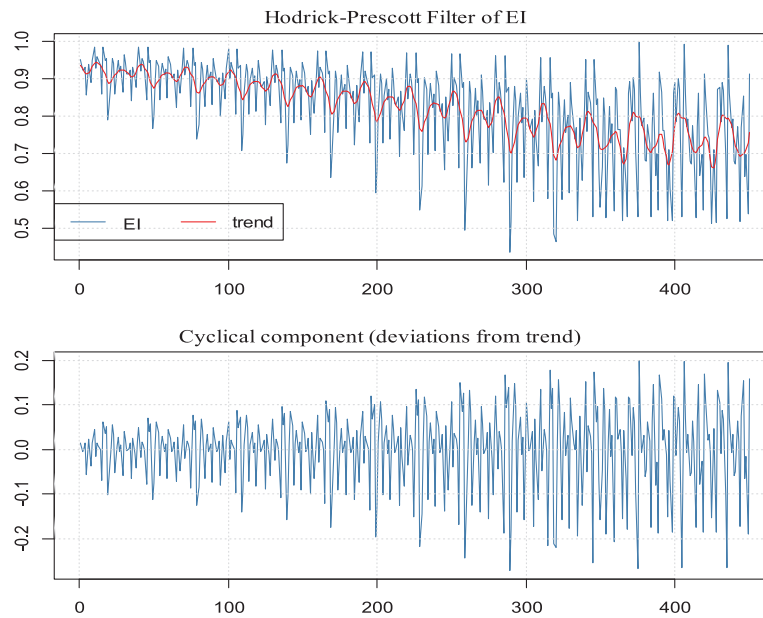
$$EC_{it} = G_{it}^C + C_{it}^C, \quad (12)$$

where  $i$  ( $i = 1, 2, \dots, N$ ) presents the number of province,  $t$  ( $t = 1, 2, \dots, T$ ) presents the period;  $EI_{it}$  is the economic inequality in  $i$ -th province at  $t$  time,  $EQ_{it}$  is the environmental quality in  $i$ -th province at  $t$  time,  $EC_{it}$  is the energy consumption in  $i$ -th province at  $t$  time;  $G_{it}^I$ ,  $G_{it}^Q$ ,  $G_{it}^C$  are the part of the trends of EI, EQ and EC, respectively; and  $C_{it}^I$ ,  $C_{it}^Q$ ,  $C_{it}^C$  are the part of the cyclical component.

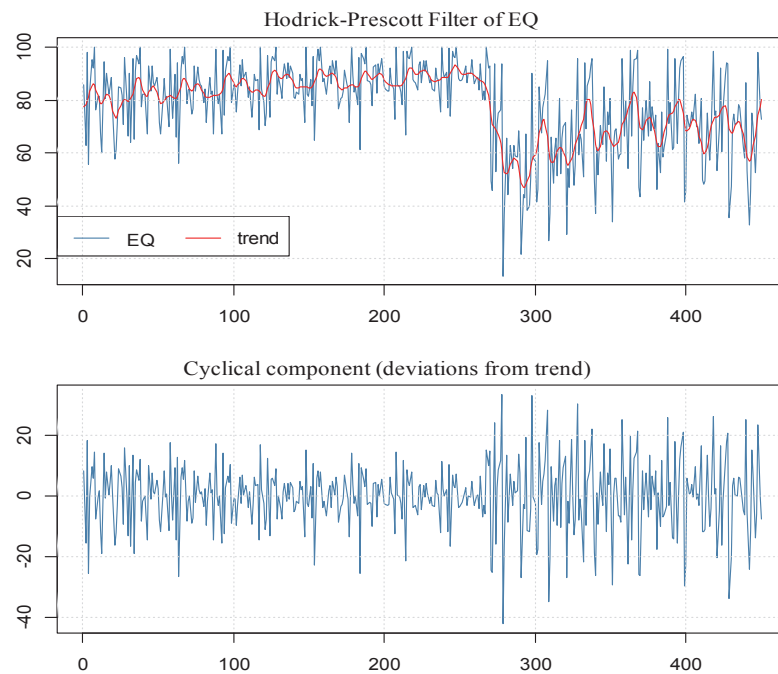
As explained by Marcet and Ravn<sup>[53]</sup> we treat EI, EQ, and EC with filtering to analyze the causal linkages between the three of them after removing the periodic fluctuation term. Figure 4, Figure 5 and Figure 6 present the results of HP filtering of EI, EQ, and EC, respectively. In general, (i) HP filtering shortens the overall change range of EI, EQ and EC, and further shows the cyclical components by removing the periodic fluctuation items; (ii) EI, EQ, and EC that only contain the trend item part are compared to the original data is more gradual; (iii) the characteristics of cyclical components from the three are obvious.

Although HP filtering method is widely used in the research of economic development, environmental protection and energy consumption, as is shown in Figure 7, the HP filtering method cannot effectively analyze the structural transformation of EI & EQ, EI & EC, and the causal relationship between EQ and EC. It is not surprising that different empirical methodologies reveal different results for the causal linkages between the two of the three variables, such as economic inequality, environmental quality, energy consumption. What's certain is that the Toda-Yamamoto causality framework with the Fourier approximation is the best choice for the study of the causality linkages of EI, EQ and EC. Of course, we also use HP filtering to test the multivariate model and the bivariate model according to Equations (7), (8) and (9) on the

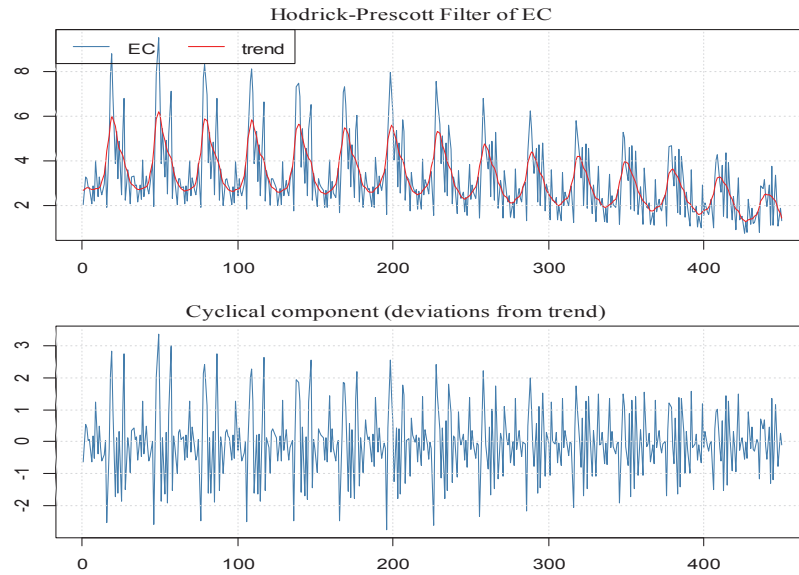
premise of eliminating the influence of the cyclical component via the Equations (10), (11) and (12). Unfortunately, the number of 30 provinces that passed the causality test is not as large as that of a simple FTY framework.



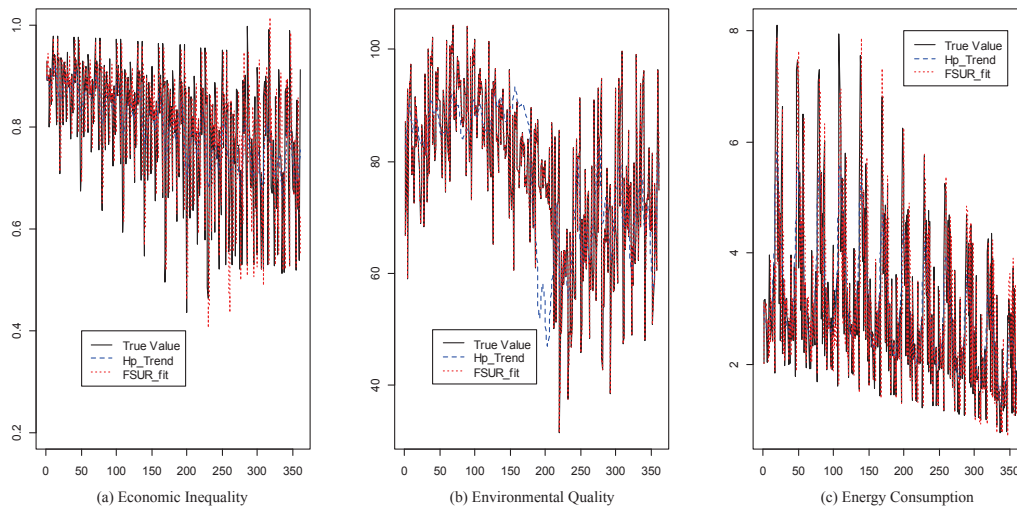
**Figure 4** The HP filtering results of economic inequality



**Figure 5** The HP filtering results of environmental quality



**Figure 6** The HP filtering results of energy consumption



Note: Hp\_Trend is the HP filtering results which apart from the cyclical component; FSUR\_fit is the fitted value from Toda-Yamamoto test with the Fourier Toda-Yamamoto method.

**Figure 7** The results of HP and FTY

## 7 Conclusion

The evolutionary characteristics of economic inequality in China from the province-level is re-explored in this paper by using the Markov chain test. We find that a continuous adjustment of the economic structure is undergone and the degree of economic inequality is weakened, moreover, the significant regional differences are presented. Obviously, provinces in the initial state at I-type are more likely to shift to the II-type and mainly in the eastern region, the uneven development of high-quality economy has shown a stage characteristic with time goes by; more provinces in central sectors are belong to II-type, they are more likely to remain



in the II-type, and in the transitional stage between inequality and relative inequality; most of the provinces in western sector belong to the III-type, they are more likely to move to the II-type with a high probability, which means that some provinces in China with a slowly development have improved their economic development level continuously, which has led to a slowing of economic inequality in recent years. The causal linkages between the two from economic inequality, environmental quality, and energy consumption is re-examined for the provinces in China during the period 2004–2018. China's provincial economies have experienced either rapid structural changes or smooth reforms in economic, environment and energy systems during this period. In order to dig the role of structural shifts in causal linkages, we first exploit the conventional Toda-Yamamoto test and then Toda-Yamamoto framework with the method of Fourier approximation. Our findings show that (i) smooth structural shifts are very important for detecting causal linkages in the studying of economic inequality, environmental quality, and energy consumption; (ii) the economy-energy and environment-energy nexus are mostly sensitive to structural transformation, it appears that more causal linkages in more provinces; (iii) employing a multivariate or bivariate framework leads to significant differences in the judgment of causal relationships. Moreover, the additional analysis points out that, on the one hand, there is a certain degree of difference in the effect size and direction of the causal relationship among the four major sectors; on the other hand, although the HP filtering method can partially reduce the effect of cyclical component the study of causal linkages, it does not effectively solve the model design and application problems, and the Toda-Yamamoto framework with Fourier approximation is more suitable in this study.

A model that allows for smooth structural shifts is required to examine the relationships between the two of economy, environment, and energy nexus. The environment-energy and economy-energy links appear to be the most sensitive to shifts in particular. The reason may be energy reforms are easier and take less time to implement than regional economy wide structural reforms. A similar argument may hold for shifts in environment sector compared to those in the aggregate economy. Taking the regional economic reforms into consideration, in provinces where regional economic development leads to energy consumption should consider their impact on the energy sector, especially; the energy-environment nexus appears to depend on economic development. Due to the energy system can influence the regional economic system and environmental system directly and indirectly, to make sound environmental and regional economic policy decisions the energy system reforms may be integrated with such policies.

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