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# The Relationship between Coordination Degree of the Water–Energy–Food System and Regional Economic Development

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**Abstract:** The sustainable development of the water–energy–food (WEF) system has gained global attention as a result of limited land resources, inadequate energy supply and growing water stress. Coordination degree is an important indicator to measure the sustainable development of the WEF system. Improving the coordination degree contributes to the sustainable development of the WEF system and affects regional economic development. The extended Cobb–Douglas function is applied to examine the relationship between coordination degree of the WEF system and regional economic development in 31 provinces of China during the period of 2007–2018. By using the system generalized method of moments (GMM) estimation, empirical results indicate that in the regions with low coordination degree, improved coordination degree of the WEF system will hinder regional economic growth. In the regions with high coordination degree, it will promote regional economic growth. The results indicate that there is a lag period for the influence of improved coordination degree on regional economic growth. When making resources management policies, shortening the lag period is conducive to achieving sustainable development and promoting regional economic development. Governments of various regions should formulate different resource management policies based on the conditions of each region and the different relationships between coordination degree of the WEF system and regional economic development.

**Keywords:** water–energy–food system; coordination degree; sustainable development; regional economic development

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## 1. Introduction

The water–energy–food (WEF) system has gained particular attention in the fields of sustainable development and resource security due to increasing demand for water, energy, and food, which results from climate change and population growth. The water–energy–food nexus as one of the focal challenges was identified by the new interdisciplinary and solution-oriented Global Change Programmer—Future Earth: "Deliver water, energy, and food for all, and manage the synergies and trade-offs among them, by understanding how these interactions are shaped by environmental, economic, social and political changes" [1]. The water–energy–food system refers to the whole network that has above functions.

The water–energy–food nexus framework, as first proposed by Hoff (2011) [2], explicitly called for actions in society, the economy, and the environment, to promote resource security and sustainable development. The WEF system has become a widely discussed topic in the academic and political areas and has increasingly driven research and policy discussion in the fields of sustainable development and resource security [3–6].

A lot of research has discussed the sustainable development of the WEF system from different perspectives and disciplines [7–10]. Nina Weitz et al. (2017) researched how the integrative environment governance literature can help to close governance gaps in the water–energy–food nexus [11]. Janez Susnik (2018) provided a quantitative modelling framework for previously qualitative descriptions of the WEF–GDP system [12]. Claudia Pahl-Wostl (2019) explained the governance challenges faced by the WEF system from different perspectives and introduced an analytical framework to identify a multi-level coordination challenge in the integrated management of the WEF system [13]. More and more research has focused on the cross-sector coordination of the WEF system [14,15].

Joanna Pardoe et al. (2017) examined how climate change is being mainstreamed into water, energy, and agricultural sector policies, and the extent to which cross-sectoral linkages enable coordinated action [16]. Christian Stein et al. (2018) analyzed how actors involved in the governance of the WEF system are embedded in social networks and discussed how that embeddedness shapes collaboration and coordination processes that are relevant for addressing sustainability challenges of the WEF system [17]. Bassel Daher et al. (2020) found that institutional mechanisms and resource allocation must be revisited to improve coordination to address the interconnected resource challenges [18]. Much research shows that improving coordination degree can improve the efficiency of resource management, enhance the ability of resources to resist risks, and can promote the realization of the sustainable development goals (SDGs) [19].

Existing research emphasizes the cross-sector coordination in the WEF system and proposes many methods to achieve cross-sectors coordination [20–23]. Some of these studies have shown that improved coordination of the WEF system has a positive impact on both society and environment [24–26]. Although studies have shown that the three resources of water, energy and food are highly related to the economy, there are still few studies on the relationship between coordination degree of the WEF system and regional economic development [27,28].

Coordination is a benign interrelationship between two (or more) systems or system elements in a proper, harmonious, and virtuous circle [29]. The coordination degree is a quantitative indicator that measures the coordination status or results between various departments of the system [30]. On the one hand, improving coordination degree will help achieve the sustainable development of the WEF system, thereby promoting economic development [31]. On the other hand, improving coordination degree requires a large amount of capital investment and will also re-allocate resources, which will have a negative impact on economic development [32,33]. Research on the relationship between coordination degree of the WEF system and regional economy has important theoretical and practical significance.

The extended Cobb–Douglas function is often used to study the influence of various factors on economic development. L. Shao (2013) studied the impact of human capital on regional economic growth with the extended Cobb–Douglas function [34]. H. Zhou et al. (2017) introduced innovation and urbanization into this function to reveal the internal mechanism of innovation output affecting economic growth through urbanization [35]. The Cobb–Douglas function is already a mature model, which is widely used when studying the influence of various factors on the regional economic growth. Therefore, this paper uses this function to determine the relationship between coordination degree of the WEF system and regional economic growth.

This paper provides a detailed analysis of the relationship between the coordination degree of the WEF system and regional economic development. The main objective was to study what kind of influence of improved coordination degree of the WEF system has on regional economic development by using the system generalized method of moments (GMM) estimation. The empirical results describe the relationship between coordination degree of the WEF system and regional economic development, and provide some enlightenment for helping governments at all levels to undertake integrated resources management policies.

## 2. Methodology

### *2.1. Study Area*

In this paper, 31 provinces and municipalities of China are taken as a study case. China's economy has been growing rapidly since the 21st century, and its GDP grew by more than 60% from 2007 to 2018 [36]. Due to the emphasis on economic growth, ecological protection and other aspects of nature have been neglected. Some side-effects are emerging in the WEF system [37]. For example, the extreme use of chemical fertilizers and pesticides directly leads to non-point agricultural pollution, damaging agricultural ecological environments [38], and even threatening the nation's food chain [39].

China is the largest energy importer. In 2019, its oil consumption was up to 68,000 b/d [40]. According to International Energy Agency (IEA) forecasts, by 2030, the energy demand of China will at least double that of 2005, half of which will come from coal [41]. The dependence of China on foreign oil and natural gas will reach 80% and 42%, respectively [40].

In terms of water resources, China has historically been facing the problem of spatiotemporal imbalance [42]. Compared with developed countries, China lags behind in water resource management technology and concepts, which directly leads to serious waste of water resources in many regions of the country. In addition, water pollution is worsening. Therefore, the supply of high-quality domestic drinking water is very scarce in some regions [43].

Taking into account all the realities related to the WEF system, the need to protect natural resources and ensure the basic living needs of water, energy, and food has become a contentious issue in municipal management. Integrated planning and management of the WEF system is crucial for maintaining economic growth.

We have divided 31 provinces and municipalities according to national policies, economic development status and geographic location [44]—eastern, central, and western regions (see Figure 1).

The eastern region includes 11 provinces and municipalities—Beijing, Tianjin, Hebei, Liaoning, Shanghai, Jiangsu, Zhejiang, Fujian, Shandong, Guangdong, and Hainan. This region is on the mainland and faces the ocean. The terrain is gentle, with good agricultural production conditions and rich water resources. It has a long history of development, superior geographical location, higher level education of the workers, stronger technical knowledge of the workforce, a solid foundation of industry and agriculture, and the most developed economy.

The central region includes 8 provinces—Shanxi, Jilin, Heilongjiang, Anhui, Jiangxi, Henan, Hubei, and Hunan. This area is located inland, contains many plains, and is flat, which is favorable for food production. Its level of economic development lies between the eastern and western regions.

The western region includes 12 provinces and municipalities—Guangxi, Chongqing, Sichuan, Guizhou, Yunnan, Tibet, Shaanxi, Inner Mongolia, Gansu, Qinghai, Ningxia, and Xinjiang. The western region covers a vast and complex territory. Most areas are highland, and water shortages are not conducive to the growth of agriculture. Due to late development history, the development level of economic and technical management is far behind the eastern and central regions.

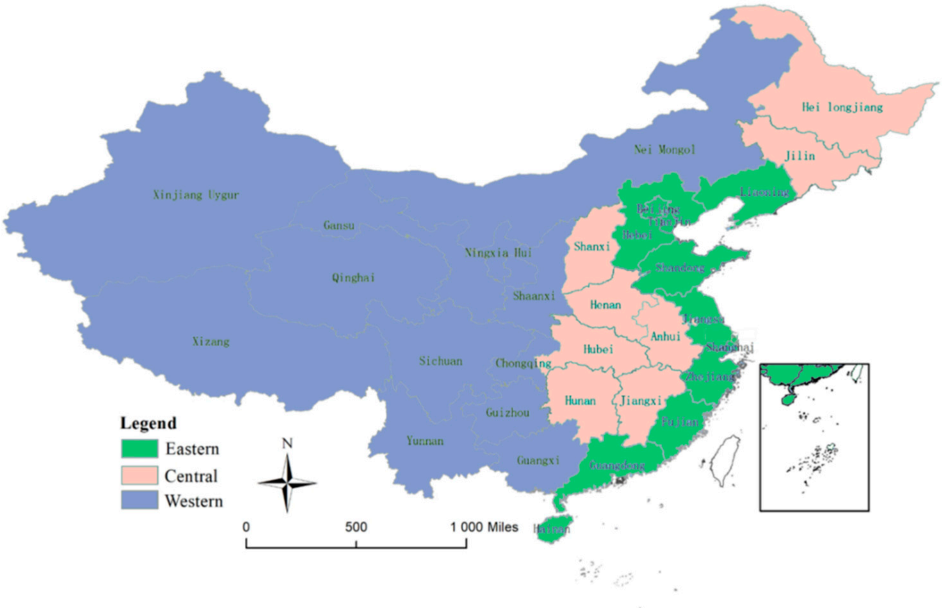


**Figure 1.** Eastern, central, and western regions in China.

### 2.2. Methods

The main method of this research was to use the extended Cobb–Douglas production model to study the contribution of factors related to economic growth. The model was modified by introducing some parameters to reflect the influence of coordination degree of the WEF system on regional economic development [45].

$$\mathrm{Y} = \mathrm{A}\mathrm{K}^{\alpha_1}\mathrm{L}^{\alpha_2}\mathrm{T}^{\alpha_3}\mathrm{C}^{\alpha_4}\mathrm{U}^{\alpha_5} \tag{1}$$

where Y represents total income; A is a constant coefficient; K is the physical capital stock; L is the amount of local labor input; T stands for technological progress; C represents the coordination degree of the WEF system; and U means the regional urbanization rate. Urbanization refers to the process of transferring rural population to cities, which promotes economic development. The ratio of the permanent urban population in a certain region (that is, the population living in an urban area for a certain period of time (more than half a year)) to the total population of this region, is used to reflect the urbanization rate [46].

In order to facilitate the analysis and interpretation of this model, the logarithms of both sides of the above model were transformed into the following form:

$$\ln \mathrm{Y} = \alpha_0 + \alpha_1 \ln \mathrm{K} + \alpha_2 \ln \mathrm{L} + \alpha_3 \ln \mathrm{T} + \alpha_4 \ln \mathrm{C} + \alpha_5 \ln \mathrm{U} + \mu \tag{2}$$

where $\mu$ is the disturbance term.

In reality, per capita GDP is a dynamic variable. It is not only affected by various current factors, but also related to some factors in the past. Therefore, the first lag term of per capita GDP was added to this model. This study used dynamic panel data; therefore, scale variables were added to the basic model:

$$\ln \mathrm{Y}_{\mathrm{it}} = \alpha_0 + \beta \ln \mathrm{Y}_{\mathrm{i(t-1)}} + \alpha_1 \ln \mathrm{K}_{\mathrm{it}} + \alpha_2 \ln \mathrm{L}_{\mathrm{it}} + \alpha_3 \ln \mathrm{T}_{\mathrm{it}} + \alpha_4 \ln \mathrm{C}_{\mathrm{it}} + \alpha_5 \ln \mathrm{U}_{\mathrm{it}} + \mu_{\mathrm{it}} \tag{3}$$

where i is the $\mathrm{i}^{\mathrm{th}}$ region, t is the year, and $\mathrm{Y}_{\mathrm{i(t-1)}}$ represents per capita GDP in $\mathrm{i}^{\mathrm{th}}$ region in $(\mathrm{t}-1)^{\mathrm{th}}$ year.

This model needs to introduce the time-delay terms of the explained variable, which may cause endogeneity problems. Traditional estimation methods (such as ordinary least square (OLS) and fixed effect (FE)) may lead to biased and inconsistent parameter estimations, and distort the economic significance of the estimated results. Therefore, this article selected the most appropriate method by comparing the estimated values of OLS, FE, and the system generalized method of moments (GMM).

### 2.3. Data Source

This paper analyzes the relationship between coordination degrees of the WEF system and regional economic development, and data were selected from 31 provinces and municipalities in China from 2007 to 2018 as empirical cases. The explained variable, explanatory variable, and control variables are shown in Table 1.

**Table 1.** Description of variables.

| | Sign | Variable | Description |
|---|---|---|---|
| Explained variable | Y | PCGDP | Per Capita GDP |
| Explanatory variable | C | CD | Coordination Degree |
| Control variables | L | LAB | The Amount of Local Labor Input |
| | K | PCS | Physical Capital Stock |
| | T | TEC | Technological Progress |
| | U | URBAN | Urbanization Rate |

The explained variable in this model reflects the economic development status of the study area. Gross domestic product (GDP) measures the value added in production of goods and services. Per capita GDP refers to portion of GDP achieved by a country in an accounting period (usually one year) to the country's permanent population, and is often used to measure the level of economic development. In this study, per capita GDP (PCGDP) data of each region were from the China Statistical Yearbook from 2008 to 2019.

The explanatory variable is the coordination degree (CD) of the WEF system. In the WEF system, coordination degree is the synergetic state between the three subsystems (water, energy, food subsystem), and the result of interaction between sectors. The coordination degree is calculated according to the evaluation index system of Xu et al. (2019) [30]; all indexes were collected from Regional Water Resources Bulletin and China Statistical Yearbook from 2007 to 2019.

There were four control variables. (1) Physical capital stock (PCS), which is represented by the fixed asset investment of the whole society. The fixed asset investment of the whole society refers to the workload and related cost changes undertaken by enterprises to construct and purchase fixed assets in a certain period of time. Increasing the fixed assets investment of the entire society can effectively promote economic growth [46]. (2) The amount of local labor input (LAB), which is expressed by employment figure. (3) Technological progress (TEC), which is represented by the number of three patents authorized in China; the three patents refer to invention patents, utility model patents, and design patents [47]. (4) Urbanization rate. The four control variables were collected from the China Statistical Yearbook from 2007 to 2018.

## 3. Results and Discussion

### 3.1. Results

By comparing the three methods (OLS, FE, and system GMM), this paper selected the most appropriate method to study the relationship between coordination degree of the WEF system and regional economic development. This paper further studied the influence of improved coordination degree on regional economic growth in different regions (the eastern, central, and western regions of China).

#### 3.1.1. Coordination Degrees of the WEF System and Their Types

In this section, the coordination degree of the WEF system was calculated first. S. Xu et al. (2019) built an index system for assessing the development level of three subsystems of the WEF system. Thus, the coupling and coordination degree of the WEF system were calculated with the coupling and coordination degree mathematical model [30]. These results showed coordination degrees of 31 provinces and municipalities during the study period from 2007 to 2018 (Figure 2).

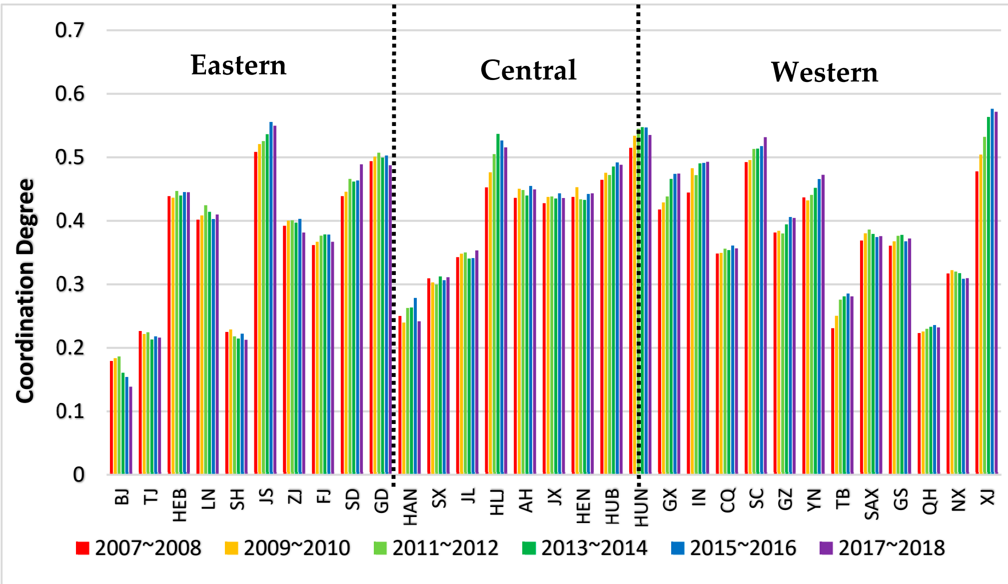


**Figure 2.** The coordination degrees of the water–energy–food (WEF) system of 31 provinces and municipalities in China.

Most studies on coordination degree [29,30] are divided into four types (Table 2).

**Table 2.** Four types of coordination degrees.

| The Type of Coordination Degree | Coordination Stage | Coordination Range |
|---|---|---|
| 1 | Low | (0, 0.4] |
| 2 | Middle | (0.4, 0.5] |
| 3 | High | (0.5, 0.8] |
| 4 | Extreme High | (0.8, 1] |

The range of low coordination degree is from 0 to 0.4; the range of middle coordination degree is from 0.4 to 0.5; the range of high coordination degree is from 0.5 to 0.8; the range of extreme high coordination degree is from 0.8 to 1. According to data in Table 2, types of coordination degrees of 31 provinces and municipalities in China are shown in Figure 3.

It can be seen from Figure 2 that from 2007 to 2018, the coordination degree of the WEF system in most regions of China fluctuated very slightly. Moreover, the overall coordination degree was low. The coordination degree of the WEF system in the central region was the highest among the three regions, and the average coordination degree of these eight provinces during the past 12 years was 0.437. The WEF system in the eastern region had the lowest coordination degree, with an average of 0.361. The coordination degree in the western region was between the central and eastern regions, with an average of 0.394.

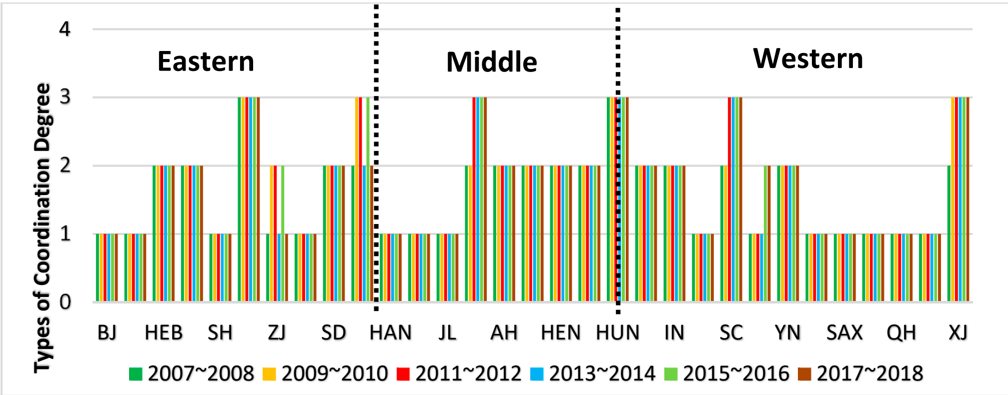


**Figure 3.** Types of Coordination Degrees of the WEF system in China.

As shown in Figure 3, there are 15 provinces in the low coordination degree, including six provinces in the eastern region (Beijing, Tianjin, Shanghai, Zhejiang, Fujian, and Hainan), two provinces in the central region (Shanxi and Jilin) and seven provinces in the western region (Chongqing, Guizhou, Tibet, Shaanxi, Gansu, Qinghai, and Ningxia). There are 11 provinces in the middle coordination degree, including four provinces in the eastern region (Hebei, Liaoning, Shandong, and Guangdong), four provinces in the central region (Anhui, Jiangxi, Henan, and Hubei) and three provinces in the western (Guangxi, Inner Mongolia, and Yunnan). There are only five provinces in the high coordination degree; one province in the east (Jiangsu), two provinces in the central region (Heilongjiang and Hunan), and two provinces in the western region (Sichuan and Xinjiang).

Coordination degree of the WEF system in many regions is still low; therefore, it is necessary to improve it for achieving sustainable development. The coordination degree is decided by the gap between development levels of three subsystems, and they have a negative correlation [30]. Taking measures to narrow the gap between the three subsystems is an effective means to improve the coordination degree of the WEF system.

#### 3.1.2. Validity of System GMM Estimation

(1) Estimated Results of OLS, FE, and System GMM Estimation

The generalized method of moments is a semi-parametric estimation method commonly used in statistics and econometrics. Traditional economic estimation methods (such as OLS, instrumental variable method, and maximum likelihood method) have their own limitations. The parameter estimator must be a reliable estimator when certain assumptions (for example, the random error term of the model obeys a normal distribution or a certain known distribution) are satisfied. GMM does not need to know the accurate distribution information of the random error term, and allows the random error term to have heteroscedasticity and serial correlation. Therefore, the parameter estimator obtained is more effective than other parameter estimation methods. The system GMM adds a horizontal equation on the basis of GMM and increases the number of moment constraints at the same time. It can effectively control the endogeneity of explanatory variables. The system GMM is widely used in parameter estimation models [48].

The system GMM estimation is sensitive to specific settings; Bond (2002) proposed a method to identify the stability of the system GMM [49]. Ordinary least square (OLS) estimates usually lead to an upward bias hysteresis coefficient, and fixed effect (FE) estimates lead to a downward bias hysteresis coefficient. If the system GMM estimation is somewhere between the FE and OLS estimations, then it is considered valid. This article simultaneously estimated the model with OLS, FE, system GMM estimations, and selected the most appropriate method by comparing the three estimated results. The estimated results of OLS, FE and system GMM are shown in Table 3.

**Table 3.** Estimated results of ordinary least square (OLS), fixed effect (FE), and the system generalized method of moments (GMM) estimation.

| Variable | OLS | FE | System GMM |
|---|---|---|---|
| Lnpcgdp (L1) | | | 0.76725091 *** |
| Lncd | −0.3817131 *** | −0.054 * | −0.17216848 *** |
| Lntec | 0.11040875 ** | 0.11532716 *** | 0.02091294 *** |
| Lnlab | −0.2748003 *** | −0.006 | −0.03266368 *** |
| Lnpcs | 0.30974107 *** | 0.45938906 *** | 0.013 |
| Lnurban | 0.73665478 *** | 0.11222916 * | 0.003 |
| Cons | 5.4470442 *** | 4.823879 *** | 1.9079572 *** |
| AR (1) | / | / | 0.0017 |
| AR (2) | / | / | 0.3 |
| Sargan | / | / | 1.0 |

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; AR (1) and AR (2) represent the results of first-order and second-order autocorrelation tests; Sargan is the result of over-recognition.

It can be seen from Table 3 that the estimated results of most control variables are significant. Technological progress, physical capital stock, and urbanization rate have a positive impact on regional economic development, while the amount of local labor input has a negative impact on regional economic development. Scientific and technological progress promotes rapid development of the national economy through positive spillover effects, reflecting the support and leading role of science and technology in regional economic development [50]. Physical capital stock remains one of the main investment tools in China. Capital accumulation is an important driving force for economic growth [51]. Urbanization can promote economic growth through four aspects: the agglomeration effect, promotion of division of labor and specialization, promotion of human capital accumulation, and sharing of convenience brought by infrastructure [52]. Urbanization has a significant positive effect on economic development. The impact of the working-age labor growth force on economic development is weakening, indicating that the period of relying solely on labor growth to drive economic growth has passed, and the quality of the labor force needs to be further improved [34]. The estimated results of the control variables were consistent with reality, and the data used in this research were true and reasonable.

In the three estimation methods, the coefficients of explanatory variables were all significant, but the results were different. The explanatory variables (coordination degree of the WEF system) were estimated to be −0.38 by OLS, −0.054 by FE, and −0.17 by system GMM. The estimated value of system GMM lay between OLS and FE, therefore system GMM was better than the other two methods when studying the relationship between the coordination degree of the WEF system and regional economic development.

(2) Reliability Analysis of System GMM Estimation

In the system GMM empirical analysis of the relationship between coordination degree of the WEF system and regional economic development, the second-order serial correlation test (AR (2)) of the differential equation was mainly used to test whether the error term of the difference transformation equation had serial correlation [49]. If the value of the AR (2) statistic test was less than the commonly used significance level, it meant that there was no serial correlation between the null hypotheses. The validity of the moment condition can be determined by the Sargan test to test the overall validity of the instrumental variable. If the value of the Sargan statistic test is large, instrumental variables are considered valid.

In Table 3, the results of AR (1) and AR (2) indicate that there was a first-order autocorrelation, but there was no second-order autocorrelation. The Sargan test showed that the null hypothesis cannot be rejected, and the lagged instrumental variable was valid. In summary, the system GMM estimation was better than the other two methods. It was used to analyze the relationship between the coordination degree of the WEF system and regional economic development in different regions.

#### 3.1.3. Estimated Results of the Eastern, Central, and Western Regions

Through the above analysis, it has been determined that the coordination degree values of the three regions, in descending order, are the central, western, and eastern. The system GMM estimation is the most appropriate method to study the relationship between coordination degree of the WEF system and regional economic development. The estimated results are shown in Table 4.

**Table 4.** Estimated results of the eastern, central and western regions.

| Variable | Eastern | Central | Western |
|---|---|---|---|
| Lnpcgdp (L1) | 0.68045629 *** | 1.3757429 *** | 0.74513613 *** |
| Lncd | −0.65257304 *** | 2.289376 ** | 0.318 * |
| Lntec | 0.003 | 0.2065328 *** | 0.006 |
| Lnlab | −0.13055859 ** | 0.928 | 0.084 |
| Lnpcs | 0.091 | 1.1715203 *** | 0.070 |
| Lnurban | 1.4788924 ** | 2.579665 *** | 0.069 |
| Cons | −1.884 | 3.727 | 2.7478819 ** |
| AR (1) | 0.0020 | 0.0394 | 0.0238 |
| AR (2) | 0.8396 | 0.5835 | 0.8181 |
| Sargan | 1 | 1 | 1 |

Note: * $p < 0.1$; ** $p < 0.05$; *** $p < 0.01$; AR (1) and AR (2) represent the results of first-order and second-order autocorrelation tests; Sargan is the result of over-recognition test.

The estimated results of the three regions in Table 4 are mostly significant. In addition, the values of AR (1) and AR (2) both show that the residuals after the difference only have first-order serial correlation and no second-order serial correlation, indicating that there is no correlation between the sequences. This is consistent with the priori assumption of no correlation between sequences in the system GMM estimation. The values of the Sargan test are all 1, which passes the over-recognition test. All these point out that the system GMM estimation method is suitable and effective in studying the relationship between coordination degree of the WEF system and regional economic development. All results are valid.

In Table 4, physical capital stock, technological progress, and urbanization rate of the three regions had a positive impact on regional economic development. In the eastern region, the amount of local labor input had a negative impact on regional economic development; in the central and western regions, it had a positive impact on regional economic development. This is because the eastern region has a more developed economy than the central and western regions. In the early stages of economic development, the increase in the number of labor forces can promote regional economic development. When the economy develops to a certain level, only by improving labor quality can it in turn promote regional economic development [34].

According to the regression results, for every 1% increase in coordination degree of the WEF coordination, the per capita GDP of the eastern, western, and central regions will change by −0.65%, 0.32%, and 2.29%, respectively.

### *3.2. Discussion*

#### 3.2.1. Relationship between Coordination Degree of the WEF System and Regional Economic Development

From Figure 2, it was ascertained that the average coordination degree of the eastern, central, and western regions from 2007 to 2018 was 0.361, 0.437, and 0.394, respectively.

The relationship between coordination degree of the WEF system and regional economic development is shown in Figure 4.

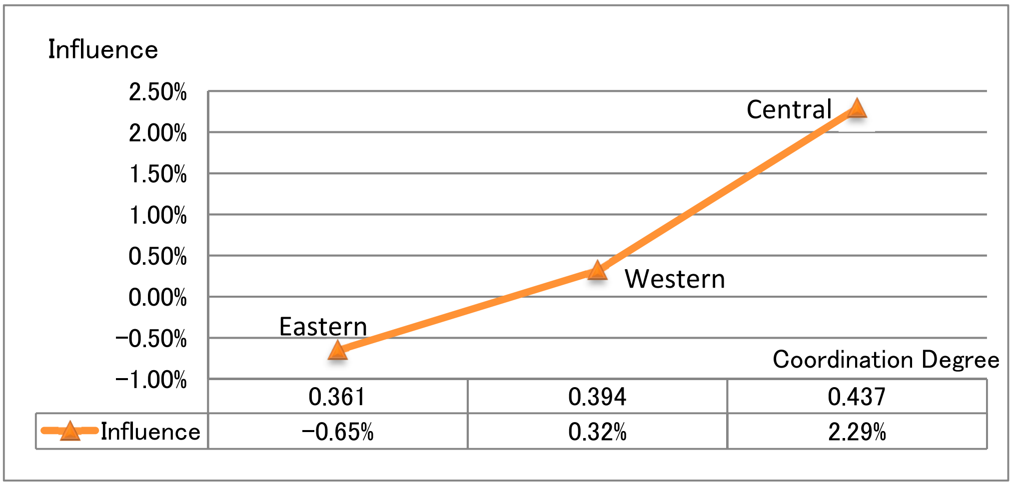


**Figure 4.** The relationship between coordination degrees and regional economic development.

Figure 4 shows that the influence of coordination degree of the WEF system on regional economic development is negative in the eastern region, while it is positive in the central and western regions. In regions with a low coordination degree, improving the coordination degree will hinder regional economic growth; in regions with a high coordination degree, improved coordination degree of the WEF system will promote regional economic development. It proves that the promotion effect is more obvious in the regions with higher coordination degree.

This is because the effective way to improve coordination degree of the WEF system is to improve the lowest development level to narrow the gap between three subsystems [30]. It requires more investment costs and takes more time from taking measures to improving the coordination degree in regions with a lower coordination degree. This often re-allocates resources in a short time and reduces the efficiency of resource utilization, which has a negative impact on regional economic development. For example, Shanghai is the international economic, financial, trade, and technological innovation center of China. Despite having a developed economy, Shanghai is one of many regions with the lowest coordination degree. In 2018, the food acreage was only 129,900 hectares, with a total output of 1.04 million tons. Per capita food production was only 58.16 kg. In the same year, the per capita food production in China was 403.38 kg, which is considerably more than that in Shanghai. However, the food yield per unit area in Shanghai is 8023 kg per hectare, which is much more than that in other provinces of China. The food acreage areas severely limit the development level of food subsystems of Shanghai. If commercial and industrial land is reduced to increase the food acreage, the value of limited land will undoubtedly be greatly reduced. On the contrary, in regions with high coordination degrees, the gap between the development levels of the three subsystems is small, thus the required investment and changes in resource allocation are small.

Moreover, the obstacles to cross-sector coordination are rigid sectoral regulation, entrenched interests and power structures, as well as established sectoral communication structures [13]. Consequently, it takes some time from taking measures to improve the coordination degree of the WEF system to having an impact on the economic development. There is a lag period for the influence of coordination degree on regional economic development. Therefore, in regions with low coordination degree, quick and effective measures and policies should be adopted to improve the coordination degree and shorten the lag period, thereby reducing investment costs. Some measures should be taken that can optimize the allocation of resources and improve coordination degree, so as to alleviate the negative impact of improving coordination degree on regional economic development.

#### 3.2.2. The Way to Improving the Coordination Degree of the WEF System in Different Regions

It can be seen from the above results that half of the research regions have low coordination degrees, and no province has an extremely high coordination degree. There is still much room for improving the coordination degree of the WEF system. It is necessary to find ways to improve coordination degree in all regions. The above analysis shows that the different measures need to be taken to improve the coordination degree of the WEF system in different regions.

Compared with the central and western regions, the eastern regions have relatively developed industrial and tertiary industries, although agriculture is weak. For example, the development level of the food subsystem in Beijing, Tianjin and Shanghai is weaker than that of other provinces and municipalities. This is because these regions are political and economic centers with high population density and small land areas. The development level gap between the three subsystems is large, making the coordination degree of these regions low. These provinces can use their advanced science and technology to improve the development level of food subsystem and narrow the gap between the three subsystems.

Due to the geographical location and climatic conditions in the eastern region, most provinces and municipalities (such as Jiangsu, Zhejiang, Shandong, Hebei, and Liaoning) have a relatively high development level of the food subsystem. However, the development levels of water and energy subsystems still lag behind. Improving water and energy efficiency use is an effective way to narrow the gap between the three subsystems.

In the central region, with the exception of Shanxi Province—which is rich in coal resources—the development level of the food subsystem in all provinces is higher than the other two subsystems. This is because the central region is facing a water shortage problem due to poor overall water quality [53]. With the rapid growth of economy, water pollution has increased [35]. In addition, energy efficiency in the central region is relatively low. Adjusting the industrial structure is the most important and realistic way to improve energy efficiency [54]. The central region can improve the development level of water and energy subsystems by reducing water pollution and adjusting the industrial structure to improve coordination degree of the WEF system.

In the western region, the development level of the water subsystem is slightly higher than the other two subsystems. Firstly, although the western region is large, most areas are restricted development zones, such as Altai in Xinjiang, the National Nature Reserve of Three Rivers Source in Qinghai, some desertification prevention areas in Inner Mongolia, some hot, dry valleys in the southwest region, Kost rocky desertification areas, and the Loess Plateau Water and Soil Erosion Prevention Area [55]. These areas are key ecological function areas. In these areas, the carrying capacity of resources and the environment is low, and the conditions for large-scale, high-intensity industrialization and urbanization are not available. This is the main reason for the underdevelopment of the energy subsystem in the western region. Secondly, due to differences in development basis, endowment conditions, and factor structure, the development level of agricultural modernization in the western region and its realization are generally lower than the overall level of China [56]. Although natural and geographical conditions restrict the development of the energy and food systems, the natural environment can be taken advantage of in order to vigorously develop clean energy such as wind power and solar energy, to improve the development level of the energy subsystem. Models of diversified and characteristic agriculture are explored based on local environmental conditions. For example, in places where land resources are concentrated (such as Xinjiang), the efficiency of agricultural production and land output can be improved through moderate scale mechanization. In regions where land sources are scarce, but characteristic agricultural resources are relatively abundant, the modernization of agriculture can be promoted through the specialized production and development of characteristic agriculture.

## 4. Conclusions

This study quantifies the relationship between the coordination degree of the WEF system and regional economic development. The results show that influences of coordination degree of the WEF system on regional economic development are different in regions with different coordination degrees. It provides guidance and direction for making resource management policies.

In order to verify the relationship between coordination degree of the WEF system and regional economic development from a dynamic perspective, this paper constructed a dynamic Cobb–Douglas model that included the lags of the explained variables. Considering that the correlation between the dynamic term and the random error term may be endogenous and there are unobservable individual effects in various factors that affect economic development, this paper used the system GMM estimation to analyze the dynamic panel data.

According to the empirical analysis results, the following conclusions can be drawn.

(1) During the study period from 2007 to 2018, the coordination degree of the WEF system in China was still low. There were still 15 provinces with a low coordination degree; 11 provinces with a middle coordination degree; and only 5 provinces with a high coordination degree. The coordination degree of the three regions, in descending order, was the central, western, and eastern regions.
(2) The system GMM estimation method is suitable for studying the relationship between the coordination degree of the WEF system and regional economic development. The results are robust and reliable.
(3) In the central, western, and eastern regions, when coordination degree of the WEF system increases by 1%, the per capita GDP changes are 2.289%, 0.318%, and −0.653%, respectively. In regions with a low coordination degree, improved coordination degree will hinder regional economic growth; in regions with a high coordination degree, improved coordination degree of the WEF system will promote regional economic development. There is a lag period for the influence of an improved coordination degree on regional economic growth. In regions with different coordination degrees, it is necessary to adapt measures to local conditions and take different measures to improve the coordination degree of the WEF system and promote regional economic development.

In the long term, improving coordination degree can not only achieve sustainable development of the WEF system, but also promote regional economic development. At present, the coordination degree of the WEF system in China is still at a low level. It is necessary to improve the coordination degree by narrowing the gap among the development level of the three subsystems. Governments of various regions need to formulate different water, energy, and food resource management policies according to the conditions of each region. Especially in areas with low coordination, it is important to find ways to quickly improve the coordination degree and shorten the lag period.

Although this paper quantifies the relationship between coordination degree of the WEF system and regional economic development, there is still more work to be done in future research; for example, determining the critical value of coordination degree of the WEF system to promote and hinder regional economic growth, and the impact of specific measures to improve coordination degree on regional economic growth.

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## References

1. Future Earth Interim Secretariat. *Future Earth 2025 Vision*; Future Earth Interim Secretariat: Paris, France, 2014.
2. Hoff, H. *Understanding the Nexus: Background Paper for the Bonn 2011 Conference: The Water. Energy and Food Security Nexus*; Stockholm Environment Institute: Stockholm, Sweden, 2011.
3. Fontana, M.D.; Moreira, F.D.A.; Di Giulio, G.M.; Malheiros, T.F. The water-energy-food nexus research in the Brazilian context: What are we missing? *Environ. Sci. Policy* **2020**, *112*, 172–180. [CrossRef]
4. Yazdani, S.; Dola, K. Sustainable City Priorities in Global North Versus Global South. *J. Sustain. Dev.* **2013**, *6*, 38. [CrossRef]
5. Degefu, D.M.; He, W.; Zaiyi, L.; Liang, Y.; Zhengwei, H.; Min, A. Mapping Monthly Water Scarcity in Global Transboundary Basins at Country-Basin Mesh Based Spatial Resolution. *Sci. Rep.* **2018**, *8*, 1–10. [CrossRef] [PubMed]
6. Zhang, Y.; Luo, P.; Zhao, S.; Kang, S.; Wang, P.; Zhou, M.; Lyu, J. Control and remediation methods for eutrophic lakes in the past 30 years. *Water Sci. Technol.* **2020**, *81*, 1099–1113. [CrossRef]
7. Saladini, F.; Betti, G.; Ferragina, E.; Bouraoui, F.; Cupertino, S.; Canitano, G.; Gigliotti, M.; Autino, A.; Pulselli, F.; Riccaboni, A.; et al. Linking the water-energy-food nexus and sustainable development indicators for the Mediterranean region. *Ecol. Indic.* **2018**, *91*, 689–697. [CrossRef]
8. Allouche, J.; Middleton, C.; Gyawali, D. Nexus Nirvana or Nexus Nullity? A Dynamic Approach to Security and Sustainability in the Water-energy-food Nexus. In *STEPS Working Paper 63*; STEPS Centre: Brighton, UK, 2014.
9. Schmidt, J.J.; Matthews, N. From state to system: Financialization and the water-energy-food-climate nexus. *Geoforum* **2018**, *91*, 151–159. [CrossRef]
10. Luo, P.; Sun, Y.; Wang, S.; Wang, S.; Lyu, J.; Zhou, M.; Nakagami, K.; Takara, K.; Nover, D. Historical assessment and future sustainability challenges of Egyptian water resources management. *J. Clean. Prod.* **2020**, *263*, 121154. [CrossRef]
11. Weitz, N.; Strambo, C.; Kemp-Benedict, E.; Nilsson, M. Closing the governance gaps in the water-energy-food nexus: Insights from integrative governance. *Glob. Environ. Chang.* **2017**, *45*, 165–173. [CrossRef]
12. Sušnik, J. Data-driven quantification of the global water-energy-food system. *Resour. Conserv. Recycl.* **2018**, *133*, 179–190. [CrossRef]
13. Pahl-wostl, C. Governance of the Water-energy-food Security Nexus: A Multi-level Coordination Challenge. *Environ. Sci. Policy* **2019**, *92*, 356–367. [CrossRef]
14. Yuan, L.; He, W.; Liao, Z.; Degefu, D.M.; An, M.; Zhang, Z.; Wu, X. Allocating Water in the Mekong River Basin during the Dry Season. *Water* **2019**, *11*, 400. [CrossRef]
15. Huo, A.; Peng, J.; Cheng, Y.; Luo, P.; Zheng, C. Hydrological Analysis of Loess Plateau Highland Control Schemes in Dongzhi Plateau. *Front. Earth Sci.* **2020**, *8*, 637. [CrossRef]
16. Pardoe, J.; Conway, D.; Namaganda, E.; Vincent, K.; Dougill, A.J.; Kashaigili, J.J. Climate change and the water–energy–food nexus: Insights from policy and practice in Tanzania. *Clim. Policy* **2017**, *18*, 863–877. [CrossRef]
17. Stein, C.; Pahl-Wostl, C.; Barron, J. Towards a relational understanding of the water-energy-food nexus: An analysis of embeddedness and governance in the Upper Blue Nile region of Ethiopia. *Environ. Sci. Policy* **2018**, *90*, 173–182. [CrossRef]
18. Daher, B.; Hannibal, B.; Mohtar, R.H.; Portney, K. Toward understanding the convergence of researcher and stakeholder perspectives related to water-energy-food (WEF) challenges: The case of San Antonio, Texas. *Environ. Sci. Policy* **2020**, *104*, 20–35. [CrossRef]
19. Davis, N. *Global Risks 2011 Report*; World Economic Forum: Cologne, Germany, 2011.
20. Rasul, G. Managing the food, water, and energy nexus for achieving the Sustainable Development Goals in South Asia. *Environ. Dev.* **2016**, *18*, 14–25. [CrossRef]
21. Scott, C.A.; Kurian, M.; Wescoat, J.L., Jr. The water-energy-food nexus: Enhancing adaptive capacity to complex global challenges. In *Governing the Nexus*; Springer: Cham, Switzerland, 2015; pp. 15–38.
22. Mu, D.; Luo, P.; Lyu, J.; Zhou, M.; Huo, A.; Duan, W.; Nover, D.; He, B.; Zhao, X. Impact of temporal rainfall patterns on flash floods in Hue City, Vietnam. *J. Flood Risk Manag.* **2020**, e12668. [CrossRef]
23. Degefu, D.M.; He, W.; Yuan, L.; Zhao, J.H. Water Allocation in Transboundary River Basins under Water Scarcity: A Cooperative Bargaining Approach. *Water Resour. Manag.* **2016**, *30*, 4451–4466. [CrossRef]
24. Li, G.; Huang, D.; Li, Y. China's Input-Output Efficiency of Water-Energy-Food Nexus Based on the Data Envelopment Analysis (DEA) Model. *Sustainability* **2016**, *8*, 927. [CrossRef]

25. Keskinen, M.; Someth, P.; Salmivaara, A.; Kummu, M. Water-Energy-Food Nexus in a Transboundary River Basin: The Case of Tonle Sap Lake, Mekong River Basin. *Water* **2015**, *7*, 5416–5436. [CrossRef]
26. Uen, T.-S.; Chang, F.-J.; Zhou, Y.; Tsai, W.-P. Exploring synergistic benefits of Water-Food-Energy Nexus through multi-objective reservoir optimization schemes. *Sci. Total. Environ.* **2018**, *633*, 341–351. [CrossRef]
27. Pahl-Wostl, C.; Bhaduri, A.; Bruns, A. Editorial special issue: The Nexus of water, energy and food—An environmental governance perspective. *Environ. Sci. Policy* **2018**, *90*, 161–163. [CrossRef]
28. Luo, P.; Mu, D.; Xue, H.; Ngo-Duc, T.; Dang-Dinh, K.; Takara, K.; Nover, D.; Schladow, G. Flood inundation assessment for the Hanoi Central Area, Vietnam under historical and extreme rainfall conditions. *Sci. Rep.* **2018**, *8*, 1–11. [CrossRef]
29. Yang, S.; Liao, C.; Zheng, Z. *Urban Ecological Environment*; Science Press: Beijing, China, 1996.
30. Xu, S.; He, W.; Shen, J.; Degefu, D.M.; Yuan, L.; Kong, Y. Coupling and Coordination Degrees of the Core Water–Energy–Food Nexus in China. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1648. [CrossRef]
31. Nhamo, L.; Mabhaudhi, T.; Mpandeli, S.; Dickens, C.; Nhemachena, C.; Senzanje, A.; Naidoo, D.; Liphadzi, S.; Modi, A.T. An integrative analytical model for the water-energy-food nexus: South Africa case study. *Environ. Sci. Policy* **2020**, *109*, 15–24. [CrossRef]
32. Cobbinah, P.B.; Erdiaw-Kwasie, M.O.; Amoateng, P. Rethinking sustainable development within the framework of poverty and urbanisation in developing countries. *Environ. Dev.* **2015**, *13*, 18–32. [CrossRef]
33. Huo, A.; Yang, L.; Luo, P.; Cheng, Y.; Peng, J.; Nover, D. Influence of landfill and land use scenario on runoff, evapotranspiration, and sediment yield over the Chinese Loess Plateau. *Ecol. Indic.* **2021**, *121*, 107208. [CrossRef]
34. Shao, L. Human Capital and Regional Economic Growth. *Popul. J.* **2014**, *36*, 74–81. [CrossRef]
35. Zhou, H.; Miao, H.; Zeng, B. Innovation Driven, Urbanization and Regional Economic Growth. *Inq. Econ. Issues* **2017**, *217*, 95–102.
36. Chen, X.; Han, J. *New Idea for Solving the Problems of "Agriculture, Rural Areas and Farmers" under the New Normal Economy*; Tsinghua University Press: Beijing, China, 2016.
37. Suocheng, D.; Dan, S.; Fujia, L.; Jiajun, L.; Fei, L.; Zhenyu, Y.; Li, Z.; Yu, L.; Rongxia, Z.; Yang, R.; et al. Study on the Resource Environment, Economy and Urbanization Situation and Green Rise Strategy in Central China. *Resour. Sci.* **2019**, *41*, 33–42. [CrossRef]
38. Mi, H.; Lu, Q. Effect of Water Investment on Agricultural Economic Growth in Shanxi Province. *J. China Agric. Univ.* **2015**, *20*, 262–267. [CrossRef]
39. Yao, C.; Yin, W.; Huang, L.; Cui, H. Spatial-Temporal Pattern and Coupling Coordination Evolution of the Vulnerability of Food Production and Consumption Ability in China. *Econ. Geogr.* **2019**, *39*, 147–156. [CrossRef]
40. Dudley, B. Bp Statistical Review of World Energy. *BP Stat. Rev.* **2020**, *6*, 00116.
41. Lefèvre, N. *Energy Security and Climate Policy: Assessing Interactions*; IEA/OECD: Paris, France, 2007.
42. Yuan, L.; He, W.; Degefu, D.M.; Liao, Z.; Wu, X.; An, M.; Zhang, Z.; Ramsey, T.S. Transboundary Water Sharing Problem: A Theoretical Analysis Using Evolutionary Game and System Dynamics. *J. Hydrol.* **2020**, *582*, 124521. [CrossRef]
43. Zhang, W. *Research on Optimal Allocation and Suggestions of Water Quantity and Water Quality in Regional Water Resources*; China University of Mining & Technology: Xuzhou, China, 2016.
44. Peng, X.; Chen, Z. Impact Evaluation on China's Western Development Policy. China Population. *Resour. Environ.* **2016**, *26*, 136–144. [CrossRef]
45. He, G.; Yang, X. The Effect of Financial Constraints on Productivity in China. *J. Quant. Tech. Econ.* **2015**, *5*, 19–35. [CrossRef]
46. Mao, L. Analysis of the Impact of China's Social Fixed Assets Investment on GDP. *Rural Econ. Sci. Technol.* **2019**, *30*, 110–111.
47. Long, X.; Wang, J. The Motivation of China's Patent Proliferation and its Mass Effect. *J. World Econ.* **2015**, *38*, 115–142.
48. Li, Q. GMM Estimation of Dynamic Panel Data Model and Its Application. *Stat. Decis.* **2010**, *16*, 161–163.
49. Bond, S.R. Dynamic Panel Data Models: A Guide to Micro Data Methods and Practice. *Port. Econ. J.* **2002**, *1*, 141–162. [CrossRef]
50. Wang, X. *On Evaluation of Coordinated Development between Regional Science and Technology Progress and Technology Progress and Economy Growth*; Jiangxi University of Finance & Economics: Nanchang, China, 2014.
51. Li, G.; Fan, L.; Feng, Z. Capital Accumulation, Institutional Changes and Agricultural Growth. *Manag. World* **2014**, *248*, 67–79. [CrossRef]
52. Liu, H.; Zhang, Q.; Yang, J. Urbanization, Spatial Spillover and Regional Economic Growth. *J. Agrotech. Econ.* **2014**, *234*, 95–105. [CrossRef]
53. Luo, P.; Kang, S.; Apip; Zhou, M.; Lyu, J.; Aisyah, S.; Mishra, B.; Regmi, R.K.; Nover, D. Water Quality Trend Assessment in Jakarta: A Rapidly Growing Asian Megacity. *PLoS ONE* **2019**, *14*, e0219009. [CrossRef]
54. Yu, B. How Does Industrial Restructuring Improve Regional Energy Efficiency? An Empirical Study Based on Two Dimensions of Magnitude and Quality. *J. Financ. Econ.* **2017**, *43*, 86–97. [CrossRef]
55. Chen, Y. An Analysis of the Industrial Policy in the Western Regions Restricted to Develop. *Reform Econ. Syst.* **2013**, *182*, 52–56.
56. Jiang, S.; Wang, Z.; Zhou, N. The Evolution, Case Analysis and Realistic Choice of Agricultural Modernization in Western China. *Issues Agric. Econ.* **2015**, *36*, 30–37. [CrossRef]