sustainability

Article

Spatial and Temporal Divergence in the Coupling Coordination of Digital Economy, Environmental Regulation and Sustainable Development: An Experience Study in China

Yunlong Cheng and Jian Yang *

School of Management, Anhui University, Hefei 230039, China
* Correspondence: yangjian@ahu.edu.cn

Abstract: The digital economy and environmental regulation are important drivers of sustainable development, and exploring the coupling of the three is important for promoting the coordinated development of regional economy, society and environment. However, integrating the three into the same system and evaluating their coupling and coordination has been little studied in academia. This research employs the entropy method with objective weighting to measure the levels of digital economy, environmental regulation and sustainable development in 30 provinces (autonomous regions and municipalities directly under the central government) in China from 2011 to 2020, invokes the concept of coupling in physics, constructs a coupling coordination degree model and identifies the spatial and temporal divergence characteristics of the coupled and coordinated development of the three subsystems. The results of the study demonstrate that: (1) the levels of digital economy, environmental regulation and sustainable development reveal a fluctuating trend of growth, with environmental regulation having the highest overall level; (2) there are spatial and temporal differences in the degree of coupling and coordination of the three subsystems, with a national coupling and coordination degree at the temporal level lying between moderate and good coordination, and showing a "W"-shaped upward trend in general and a "chain" at the spatial level; (3) There is a significant spatial autocorrelation in the degree of coupling coordination, with a localized "high–high" and "high–high" pattern. Based on the above results, the article concludes with suggestions to enhance the development level of each subsystem, providing thoughts for the improvement of the coupling and coordination degree of the three in the later stage.

Keywords: digital economy; environmental regulation; sustainable development; coupled coherence

check for updates

Citation: Cheng, Y.; Yang, J. Spatial and Temporal Divergence in the Coupling Coordination of Digital Economy, Environmental Regulation and Sustainable Development: An Experience Study in China. *Sustainability* **2023**, *15*, 9649. https://doi.org/10.3390/su15129649

Academic Editors: Ranga Chimhundu, Angela Siew Hoong Lee and Ka Ching Chan

Received: 9 May 2023
Revised: 5 June 2023
Accepted: 14 June 2023
Published: 16 June 2023

1. Introduction

China, as the world's second largest economy, has taken the initiative to assume international responsibility for climate change in the face of the increasingly serious global carbon emissions situation. At the 75th session of the UN General Assembly, China proposed for the first time a "double carbon" target, i.e., to achieve peak CO_2 emissions by 2030 and carbon neutrality by 2060. These goals will provide direction for China to upgrade its industrial structure, promote the development of new industries and accelerate the use and development of clean and efficient energy sources, laying the foundation for the eventual reduction of pollutant emissions and sustainable improvement of the ecological environment. With the rapid development of communication technology and the market-based allocation of factors, the emergence of a digital economy has led to the renewal of production and business management activities. The year 2016 saw the inclusion of the "digital economy" as an important element of the G20 Summit in Hangzhou for the first time, and in 2017, the term "digital economy" was written into the Government Work Report for the first time, putting forward new requirements to promote the in-depth development of "Internet+" and accelerate the growth of the digital economy. In 2022, the size of China's digital economy rose from CNY 11 trillion at the beginning of the 13th Five-Year Plan to CNY 45 trillion, accounting for 39.8% of the GDP, and it is foreseeable that the proportion of the digital economy in China will continue to rise. At the same time, the 14th Five-Year Plan and the outline of the 2035 Visionary Goals will be divided into separate chapters to express the content of the digital economy. The outline pointed out that efforts should be made to create new advantages in the development of the digital economy, promote the deep integration of digital technology and the real economy, empower the transformation and upgrading of traditional industries and promote the level of digital government construction to create a good digital ecological environment. The development of the digital economy has given rise to a new model of economic growth, but it has also led to the accelerated penetration of digital technology into different areas of China's economic and social development, which has contributed to socio-economic development and environmental protection through the efficient allocation and integration of resources.

With the advancement of economic globalization, scientific and technological informatization and social knowledge, sustainable development has gradually become a common goal for all countries to strive for [1]. While China's industrialization process is accelerating, the resources and environment are creating rigid constraints on the economy and society in the context of the new normal development. Polluting enterprises with high energy consumption, high pollution and high emissions using coal as the main raw material are causing a certain degree of damage to the environment and economic benefits [2]. How to deal with the relationship between environmental protection and economic growth focuses on the quality of economic development and the efficiency of resource use. Therefore, transforming the mode of economic development, making strategic adjustments to the economic structure and ultimately realizing the establishment of a resource-saving and environmentally friendly society have become important driving forces for the sustainable development of human economy and society [3]. With the current ecological and environmental problems becoming increasingly serious, the digital economy—as the "gas pedal" and "stabilizer" of China's economic growth momentum under the new normal—the use of big data, artificial intelligence and other means to promote the combination of digital technology and the traditional real economy [4], to achieve the "resources-products-pollution emissions" of extensive production into "low-carbon" flexible production and to form "big data + big ecological" integrated development [5], become important internal driving forces to enhance the efficiency of green innovation. In addition, as the basis and condition for enhancing the comprehensive national power of sustainable development, the study of the coupled and coordinated role played by these factors in the process of sustainable development is of great significance in promoting high-quality economic, social and environmental development among other countries and regions.

China's digital economic industry is growing in scale as the infrastructure and development of the digital economy has increased significantly, and its goal of "stabilising growth and promoting transformation" suggests a solution for the replacement of traditional environmentally polluting industries. In addition, sustainable social development cannot be achieved without the support of economic, environmental, social and governance factors. Therefore, through the full release of digital technology, we can provide technical support for precise, scientific and legal pollution control, modernize the ecological environment and ecological governance, improve the living environment and quality of life and achieve sustainable social development. Therefore, the evaluation of the digital economy, environmental regulation and sustainable development plays an important role in the construction of China's overall goal of "ecological priority, conservation and intensive, green and low-carbon development". This study aims to evaluate the level of the digital economy, environmental regulation and sustainable development in China, incorporate a coupled coordination model, elaborate on the spatial and temporal trends of the coupled coordination of the three systems, analyze the differences in the coupled coordination of different regions and finally make recommendations from the perspective of improving the development of the three systems.

The possible marginal contributions of this paper are as follows: Firstly, it innovatively incorporates the digital economy, environmental regulation and sustainable development into the same evaluation system, enriching the existing literature. Secondly, as the digital economy, environmental regulation and sustainable development are important factors in current society, this paper examines the coupling and coordination relationships between the three based on the introduction of the coupling concept in physics, and uses the Moran index to analyze the degree of spatial and temporal variation in the coupling and coordination in different regions from the perspective of spatial correlation.

The overall structure of this paper is as follows: Section 2 compares and evaluates the contents of the relevant literature on the digital economy, environmental regulation and sustainable development; Section 3 describes the specific evaluation indicators, methods and the introduction of relevant formulas for the three subsystems; Section 4 describes the evaluation results of the development levels of the three systems, respectively, and analyzes the changing trends of the coupling coordination degree in China from the perspective of time and space; Section 5 analyzes the spatial correlation of the coupling coordination degree from Section 4 and conducts a spatial correlation analysis; Section 6 presents a summary of the conclusions and puts forward relevant policy recommendations.

2. Literature Review

2.1. Digital Economy and Environmental Regulation

Environmental imbalance is an unavoidable problem in China's industrialization process [6], and the digital economy, as an important engine for China's high-quality economic development [7,8], advocates for the construction of a resource-saving and environmentally friendly economic development model [9], putting forward new requirements for the problems of "high pollution, high emissions and low efficiency" that exist in China's traditional industrial structure. Research shows that the digital economy mainly promotes the efficient use of resources in each region through enabling technological innovation and relying on core domain technologies such as the Internet and artificial intelligence [10], and achieves coordinated regional development with real-time, interactive and open characteristics. This requires a strict and standardized combination of environmental policy tools to be formulated by government departments in the process of industrial development at all levels, fully utilizing various digital technologies, promoting the upgrading of regulatory instruments and improving regulatory effectiveness [11]; forming "industry barriers" to existing or upcoming energy-consuming industries; and changing the production method that uses capital, labor and land as traditional industrial factors [12]. In addition, the implementation of strict environmental policies by the government can increase the production costs of enterprises, but when environmental regulations are properly implemented, they can stimulate enterprises to clarify the direction of technological change and thus generate "innovation compensation" to compensate for the short-term increase in production costs, thus achieving the joint improvement of environmental protection, innovation level and economic development [13,14]. Ultimately, a series of environmental regulations will force enterprises to integrate digital resources; reduce the proportion of polluting output; form "digital content, digital intelligence, and digital industry" as the main production factors; and improve the total factor productivity of industry, which will become an important initiative for the development of the digital economy [15].

2.2. Digital Economy and Sustainable Development

The concept of sustainable development was first proposed by the United Nations in 1987 [16], which mainly calls for the development of all aspects of society to meet the needs of the present while not endangering the normal needs of future generations, and makes a clear plan for the way forward for human social development. More studies have taken the refinement of the concept of sustainable development as a starting point [17,18], and gradually expanded to the analysis of its mechanism of action and exploration of its influencing factors in social, economic and ecological dimensions [19,20]. Currently, China is facing a critical period of transformation from industrial civilization to ecological civilization [21], and in the context of sustainable development, the digital economy realizes social governance through market transformation, financial quality and efficiency improvement, and value reconstruction, which provides the direction of future changes to the quality of social development, market operation mechanism and industrial structure adjustment [22,23]. However, there are still problems such as the "digital divide" between regions, network information security and imperfect regulatory laws, which to a certain extent reveal that digital governance lags behind the development of society in terms of system and theory [24,25]. In addition, in terms of sustainable economic development, the digital economy mainly empowers traditional labor methods to be digitalized, intelligent and networked; reduces energy consumption in production; and promotes the integration of Internet technologies with economic systems to efficiently invest limited resources in production activities and form economies of scale, mainly by improving the efficiency of matching supply and demand in the free flow of factors [26,27]. Finally, digital transformation, relying on information technology and changes in the internal and external environment [28], can accurately identify ecological and environmental problems, promote the construction of a dynamic system for monitoring ecological and environmental data, continuously improve green innovation capacity, and promote the synergistic development of the green economy and the digital economy [29–31].

2.3. Environmental Regulation and Sustainable Development

Environmental regulation is a policy system consisting of four dimensions: command and control, market incentives, social participation and voluntary action [32]. According to Pigou's theory of welfare economics, environmental taxation can promote the internalization of external uneconomical environmental pollution by enterprises and promote more "environmentally friendly" production decisions, thus achieving a win-win situation for both market defects and social welfare [33]. In the current context of increasing pressure on economic, social and ecological development, only by taking the path of sustainable development and making the rate of human demand for resources lower than the rate of regeneration of the resources themselves and their substitutes can we realize the construction of an ecological civilization with the aim of harmonious coexistence between human beings and themselves, human beings and nature and human beings and society [34], and then finally realize the goal of sustainable development—the balance of economy, society and ecology [35]. In addition, the impact of environmental regulation on sustainable development is not limited to the macro-level effects on industrial restructuring [36], reduction of pollution emissions [37] and resource utilization enhancement in the traditional sense [38], but more micro-specific levels such as labor employment [25,39], urban–rural income gaps [40], high and low commodity prices [41] and public health and safety [42], which generate corresponding mechanisms of action.

A review of the literature shows that there is a wealth of previous research on the two causal relationships between the digital economy, environmental regulation and sustainable development, exploring the unidirectional influence or coupling of a single subsystem on another subsystem, which is of strong reference value for this study. However, as the digital economy, environmental regulation and sustainable development are important building blocks of China's "new development pattern", few studies have integrated the three subsystems into the same framework and explored their coupling and coordination. Therefore, this paper takes 30 provinces (autonomous regions and municipalities directly under the central government) in China as the research object (Tibet, Hong Kong, Macao and Taiwan are not included in the scope of this study due to serious data deficiencies), selects the data from 2011 to 2020 when the development level of the three subsystems was improving rapidly and constructs an evaluation index system for the three subsystems based on the coupling mechanism of digital economy, environmental regulation and sustainable development. The spatial and temporal distribution of the coupling and coordination relationship is explored, with a view to providing a reference for decision making to promote the coupling and coordination degree of digital economy, environmental regulation and sustainable development.

3. Research Design

3.1. Analysis of the Coupling and Coordination Mechanism of a Digital Economy, Environmental Regulation and Sustainable Development

The coupling and coordination of the digital economy, environmental regulation and sustainable development means that the three subsystems interact with each other in such a way that the overall effect is greater than the effect of each subsystem. The theoretical framework for the coordination of the three subsystems is as follows: the digital economy is the basis for the implementation of environmental regulation. The digital economy has an impact on environmental regulation through industrial upgrading, technological support and optimization of resource allocation. By introducing digital technologies such as big data, the Internet of Things and traditional industries, the digital economy has given rise to a new economic development model that makes full use of cloud computing technology, taps into market demand, optimizes resource allocation and reduces pollutant emissions.

Environmental regulation is a guarantee for the development of the digital economy, which can use soft or hard constraints to force the original industry to change its development concept, explore green technology innovation to promote an advanced and rationalized industrial structure, promote the establishment of cooperation and exchange mechanisms between various innovative subjects to reduce pollution technology, expand the means and channels of environmental monitoring, enhance the transparency of environmental information and alleviate the problem of information asymmetry between various subjects. This will result in a two-way interaction between "environmental management" and "digitalisation", which will enhance the digital innovation capacity of the region while curbing carbon emissions and reducing the pressure on resources and the environment.

Sustainable development is the ultimate goal of the digital economy and environmental regulation. The economy and the environment are important coupling factors for sustainable development, and the previous crude economic production model has placed a large burden on the regional environment, which is not in line with the goal of sustainable development. Digital technology uses the Internet as a medium to exchange resources and, thus, reduce transaction costs. Under the constraints of environmental regulation, different industries integrate resources while promoting changes in industrial models, increasing investment in research and development, improving production processes, enhancing green production efficiency and environmental management and achieving the harmonious co-existence of the economy, environment and society, in line with the requirements of sustainable development theory. Therefore, it is important to integrate the digital economy, environmental regulation and sustainable development into the same coupling system to maximize the effectiveness of all three in order to achieve the strategic goal of high-quality development in China.

3.2. Evaluation Index System Construction

Regarding the evaluation of the digital economy, the academic community has not yet formed a unified opinion. In this paper, the development level of China's digital economy is measured on the basis of Zhao Tao (2020) [43] and other scholars. In addition, from the perspective of regulation cost in environmental regulation, industrial wastewater emission, industrial sulfur dioxide emission and industrial smoke (dust) emission were selected as indicators. Finally, from the concept of sustainable development, indicators were selected based on the economic, ecological and social perspectives. Finally three major subsystem evaluation index systems were formed, and the entropy value method was applied to evaluate each subsystem (Table 1).

Table 1. Evaluation index system of digital economy, environmental regulation and sustainable development.

Subsystem	Primary Indicators	Secondary Indicators	Indicator Properties
Digital economy	Internet output	Total telecom services per capita (billion CNY)	+
	Internet penetration	Rate number of Internet broadband access users	+
	Number of employees in the Internet industry	Percentage of employed persons in urban units of the information transmission, software and information technology service industry (%)	+
	Number of Internet users	Number of cell phone users (units per 100 people)	+
	Digital Inclusive Finance Index	Peking University Digital Inclusive Finance Index	+
Environmental regulation	Regulation cost	Industrial wastewater emissions (million tons)	-
		Industrial sulfur dioxide emissions (million tons)	-
		Industrial smoke (dust) emissions (million tons)	-
Sustainable development	Economy	GDP per capita (10,000 RMB/person)	+
		Value added of tertiary industry (billion CNY)	+
		Per capita disposable income of all residents (CNY)	+
		Urbanization rate (%)	+
	Ecology	Water consumption per capita (cubic meters)	-
		Industrial pollution control investment as a proportion of secondary industry output value	+
		Forest coverage rate (%)	+
		Park green space per capita (square meters)	+
		Harmless domestic waste treatment rate (%)	+
	Social	Urban registered unemployment rate (%)	-
		Number of urban basic medical insurance participants at the end of the year (million)	+
		Number of medical and health institutions	+
		Average number of students enrolled in higher education institutions per 100,000 population (persons)	+
		Public library floor space per 10,000 population (square meters)	+
		Public transportation vehicles per 10,000 people (standard units)	+

3.3. Kernel Density Function

The kernel density function is a commonly used non-parametric method for estimating the probability density function of a random variable, using the position and shape of the distribution of the curve to elaborate the trend of change in the object of study. In this study, the kernel density estimation method was used to plot the kernel density curves of digital economy, environmental regulation and sustainable development level, and the probability distribution and dynamic evolution of each of the three subsystems were analyzed using Gaussian kernel functions. The equations are shown in (1) and (2):

$$f(x) = \frac{1}{nh}\sum_{i=1}^{n} K\left(\frac{X_i - \overline{x}}{h}\right) \tag{1}$$

$$K(x) = \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{x^2}{2}\right) \tag{2}$$

where n represents the number of provinces studied; h represents the bandwidth of the kernel density curve; $K(\cdot)$ represents the kernel function of the smoothing transformation; X_i represents the observed values; and $\overline{x}$ represents the mean of the observed values. The choice of bandwidth directly affects the degree of smoothing of the kernel density curve, based on study [44], showing that the bandwidth is a function of the number of provinces studied, as follows:

$$h = (\frac{4}{3n})^{\frac{1}{5}} \approx 1.06n^{-\frac{1}{5}}$$

3.4. Coupling Coordination Degree Model

Coupling is a physical concept that refers to the phenomenon that there is some connection between two or more systems or forms of motion that affect each other to the point of union through various interactions, and has been applied in the fields of economics, geographic science and other disciplines. The degree of coupling coordination refers to the degree of interaction and coordination between two or more systems, and the calculation formula is shown in (3)–(5).

$$C = \frac{3 \times \sqrt[3]{S_1 \times S_2 \times S_3}}{S_1 + S_2 + S_3} \tag{3}$$

$$T = \alpha \times S_1 + \beta \times S_2 + \gamma \times S_3 \tag{4}$$

$$R = \sqrt{C \times T} \tag{5}$$

where S_1, S_2 and S_3 represent the integrated level of digital economy, environmental regulation and sustainable development, respectively; C represents the coupling degree of the three, and takes the value between [0, 1], and the larger the value, the higher the coupling degree; T represents the comprehensive coordination index; a, b and r represent the weight coefficients. With reference to previous studies [45], all three coefficients were taken as 1/3; and R represents the coupling coordination degree, and its determination criteria are shown in Table 2.

Table 2. Criteria for classifying the type of coupling coordination.

Coupling Coordination	[0, 0.2)	[0.2, 0.4)	[0.4, 0.6)	[0.6, 0.8)	[0.8, 1)
Type	Severe dissonance	Primary coordination	Moderate coordination	Good coordination	High quality coordination

3.5. Spatial Autocorrelation

The Moran index is an important index to examine the spatial correlation, and the spatial autocorrelation test can be used to study the dependence of the distribution pattern of the coupling coordination of the three subsystems. Firstly, the global Moran index was measured in this paper, and its value ranged from −1 to 1. A value greater than 0 indicated positive autocorrelation, one less than 0 indicated negative autocorrelation, one equal to 0 indicated no autocorrelation, and a larger value indicated stronger spatial correlation. Secondly, the local Moran index was calculated and a scatter plot was drawn to understand the spatial correlation characteristics of the coupling coordination degree among provinces. The local spatial agglomeration types can be divided into four types: "High–High (high-coupling provinces are surrounded by high-coupling provinces), High–Low (high-coupling provinces are surrounded by low-coupling provinces), Low–Low (low-coupling provinces are surrounded by low-coupling provinces) and Low–High (low-coupling provinces are surrounded by high-coupling provinces)". The formula for calculating the Moran index is shown in Equation (4).

$$Moran's\ I = \frac{\sum_{i=1}^{n} (y_i - \overline{y}) \sum_{j=1}^{n} W_{ij}(y_j - \overline{y})}{\frac{1}{n}\sum_{i=1}^{n} (y_i - \overline{y})^2 \sum_{i=1}^{n} \sum_{j=1}^{n} W_{ij}} \tag{6}$$

y_i, y_j represent the observations, $\overline{y}$ represents the mean value, n represents the number of regions and W_{ij} represents the spatial weight matrix; in this paper, the neighboring spatial matrix was selected for analysis.

3.6. Data Sources

The research period of this paper was 2011–2020. The original data of digital economy were from the China Statistical Yearbook and the Digital Inclusive Finance Index promulgated by the Digital Finance Research Center of Peking University, the original data of environmental regulation were from the China Environmental Statistical Yearbook and the China Urban Statistical Yearbook and the original data of sustainable development were from the China Statistical Yearbook and the China Environmental Statistical Yearbook. In view of the availability of data, the study covered 30 provinces (autonomous regions and municipalities directly under the central government) in China, and the Tibet Autonomous Region, Hong Kong, Macao and Taiwan had too much missing data, so they were not included in this study.

4. Results and Analysis

4.1. Kernel Density Distribution of Development Level of Each Subsystem

Before studying the coupled and coordinated relationship among digital economy, environmental regulation and sustainable development, the entropy value method was applied to calculate the integrated level of the three systems, and a total of four years, 2011, 2014, 2017 and 2020, were selected to construct the kernel density distribution of each subsystem to understand the dynamic evolution of the evaluation index of each system.

As shown in Figure 1a, the overall digital economy development distribution curve from 2011 to 2020 shows a trend of "right-shift-left-shift", indicating the evolution of the regional digital economy development level from rising to a small decline during the study period; the height of the peak shows a rise followed by a decline, and the width of the peak shows a characteristic of "narrowing-expanding-then narrowing". The peak height shows a rise and then a decline, and the width shows the characteristics of "shrink-expand-shrink again", with the right trailing extension showing a gradual convergence, and another small peak and valley at the end of the curve, indicating that the difference in the level of digital economy development between regions has moderated, but there is still the phenomenon of unipolarity. As shown in Figure 1b, the center of the distribution curve of the environmental regulation index from 2011 to 2020 moved to the right year by year, and the curve rose the fastest in 2020, indicating that the intensity of environmental regulation in China has been increasing; the height of the main peak shows a trend of first falling and then rising.

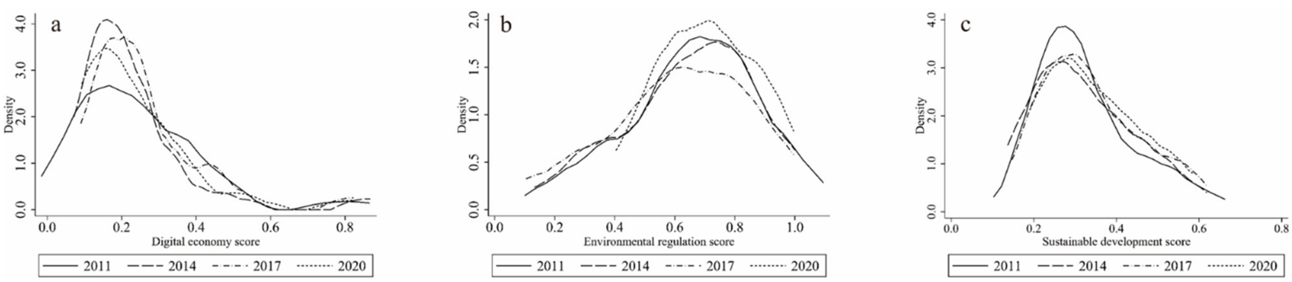

Figure 1. Kernel density distribution of digital economy, environmental regulation and sustainable development levels. (**a**) Kernel density distribution of digital economy; (**b**) Kernel density distribution of environmental regulation; (**c**) Kernel density distribution of sustainable development levels.

In some years, the main peak and small side peaks coexist, but gradually change to single-peak distribution with time change, the width of the curve shows "expansion-convergence" and the right trailing phenomenon is alleviated, indicating that the absolute difference in environmental regulation intensity within each region is reduced, and the polarization phenomenon has been suppressed to some extent. As shown in Figure 1c, the distribution curve of sustainable development level shows a gradual rightward shift, the height of the main peak shows the characteristic of "decrease-increase-decrease", the width of the curve shows the process of "convergence-expansion", there is no obvious right trailing characteristic and the sample years for all of the curve were dominated by a single peak. This indicates that the sustainable development level of each region increased to a certain extent during the study period, but there are still large differences between regions and the spatial aggregation degree decreased.

4.2. Analysis of Coupling Coordination Degree Results

4.2.1. Time Level

From 2011 to 2020, the coupling coordination degree of digital economy, environmental regulation and sustainable development in China was moderately coordinated, with an average value of 0.584. The fluctuation trend of the curves in each region was similar, and the overall distribution was "W"-shaped, indicating that there was a gap in the coupling coordination index between different years. The mean value of coupling coordination in the eastern region was distributed between 0.634 and 0.676, which is higher than the national average and in a good coordination grade, indicating that the coupling and coordination of the three is developing in a good manner. Although the eastern region has problems such as higher population density and environmental pollution, it is able to rely on diversified economic and administrative means to promote the upgrading of the region's crude industrial structure and the formation of a sound science and technology and industrial supply chain, which can improve the total factor productivity of the industry and reshape a new model of environmental governance and economic operation development with the support of digital resources, ultimately achieving green and sustainable development. On the contrary, the central, western and northeastern regions of China are relatively backward in coupling coordination due to the existence of differences in industrial structure, economic foundation and factor endowment (Figure 2).

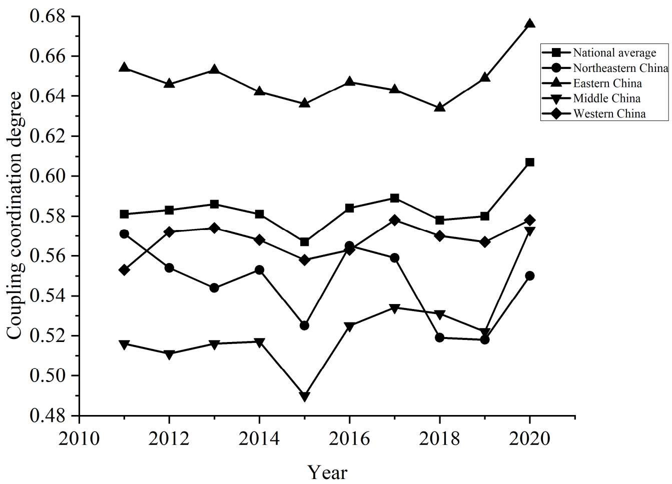

Figure 2. Temporal trend of coupling coordination.

4.2.2. Spatial Dimension

Arcgis was used and based on the natural breakpoint method to visualize the numerical spatial distribution of coupling coordination, and only the distributions for 2011, 2015 and 2020 are shown in this paper. Overall, the coupling coordination degree was located in the above-moderate coordination class, and there was spatial heterogeneity in the values between regions, but little variation in the year of the coupling coordination type. Among them, Beijing always belonged to the high quality coordination stage during the study period, as the capital city can attract more capital, personnel and technology to promote the maximum productivity of resource factors, coupled with the early implementation of various policy pilot work, the introduction of advanced science and technology to achieve pollution reduction and emission reduction and realizing the transformation from the original crude economic growth model to an intensive economic growth model, which in turn promotes the sustainable development of economy, society and environment. In addition, the coupling coordination of Tianjin, Shanghai, Zhejiang, Fujian, Guangdong, Sichuan and Shaanxi was always in the good coordination stage; Chongqing, Jiangsu and Qinghai provinces and cities increased from medium coordination in 2011 and 2015 to good coordination in 2020; Ningxia and Hubei provinces decreased to moderate coordination from good coordination in 2011 and 2015; most of the central and western regions and the northeastern region were moderately coordinated in terms of coupling coordination, with relatively stable changes in type across years (Figure 3).

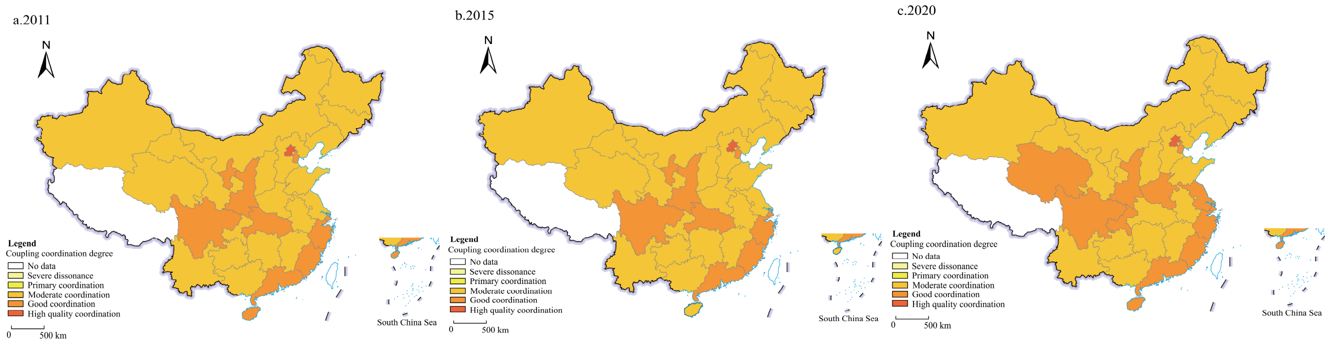

Figure 3. Spatial distribution of coupling coordination. (**a**) Spatial distribution in 2011; (**b**) Spatial distribution in 2015; (**c**) Spatial distribution in 2020.

5. Spatial Autocorrelation

5.1. Global Spatial Autocorrelation

Using the binary spatial adjacency weight matrix (two regions were assigned a value of 1 when they were adjacent and 0 when they were not), the global Moran index of coupling coordination degree was measured for 30 provinces and cities. The results (Table 3) show that the global Moran indexes of the coupling and coordination degree of digital economy, environmental regulation and sustainable development in China during 2011–2020 were all greater than zero and passed the significance test, indicating that the coupling and coordination degree of the three show the characteristics of a "spatial club". Specifically, the global Moran index of each year had a large trend, the overall trend showed a "W"-shaped distribution and the global Moran index of the coupling coordination degree of each system in the three time periods of 2011–2012, 2014–2015 and 2018–2019 was greater than zero. The clustering effect of the coupling coordination of each system increased in the three time periods of 2011–2012, 2014–2015 and 2018–2019, while the dispersion phenomenon appeared in the remaining years.

Table 3. Global autocorrelation index from 2011 to 2020.

Year	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Moran's I	0.198	0.200	0.154	0.143	0.181	0.156	0.128	0.139	0.207	0.183
p-Value	0.027	0.023	0.052	0.063	0.036	0.054	0.087	0.073	0.023	0.032

5.2. Local Spatial Autocorrelation

The global Moran index can only represent the spatial autocorrelation status of coupling coordination as a whole, and cannot reflect the coupling coordination heterogeneity across regions. Therefore, the local Moran indices for 2011, 2014, 2017 and 2020 (Figure 4a–d) were calculated and local Moran index scatter plots were drawn to characterize the local spatial agglomeration of the coupled coordination degree of digital economy, environmental regulation and sustainable development in each region of China. As can be seen from Figure 4, the coupling coordination coordinates of more provinces and cities were located in the first and third quadrants, indicating that the national coupling coordination degree showed a spatial clustering phenomenon, i.e., regions with high coupling coordination degree drive the coupling degree of surrounding regions to increase, and regions with low coupling coordination degree cause the coupling degree of surrounding regions to decrease.

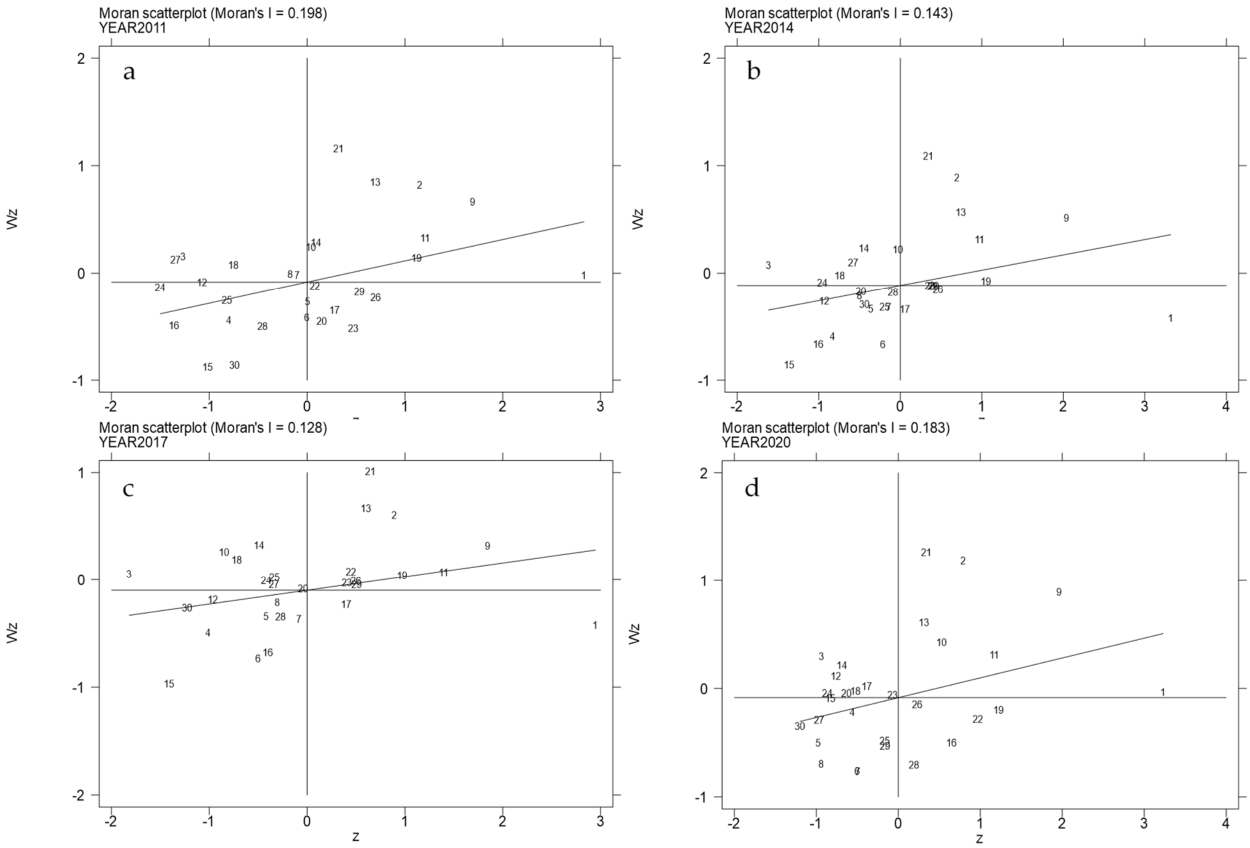

Figure 4. Local Moran Index Scatter Plot for 2011, 2014, 2017, 2020. Note: 1—Beijing, 2—Tianjin, 3—Hebei, 4—Shanxi, 5—Inner Mongolia, 6—Liaoning, 7—Jilin, 8—Heilongjiang, 9—Shanghai, 10—Jiangsu, 11—Zhejiang, 12—Anhui, 13—Fujian, 14—Jiangxi, 15—Shandong, 16—Henan, 17—Hubei, 18—Hunan, 19—Guangdong, 20—Guangxi, 21—Hainan, 22—Chongqing, 23—Sichuan, 24—Guizhou, 25—Yunnan, 26—Shaanxi, 27—Gansu, 28—Qinghai, 29—Ningxia, 30—Xinjiang. ((**a**): Local Moran Index Scatter Plot for 2011; (**b**): Local Moran Index Scatter Plot for 2014; (**c**): Local Moran Index Scatter Plot for 2017; (**d**): Local Moran Index Scatter Plot for 2020).

In addition, the local Moran index distribution map can be used to classify the agglomeration situation from the first quadrant to the fourth quadrant into four types: High–High, Low–High, Low–Low and High–Low. Specifically, the spatial agglomeration range of the "High–High" type was mainly concentrated in the eastern region, indicating that the coupling coordination in the eastern region of China initially formed agglomeration and spillover effects, and the differences among provinces were gradually decreasing. The remaining three agglomeration types were more concentrated in the regions with lower economic development in China, and the effect of the spillover effect on other regions was not obvious due to the low degree of coupling and coordination in each region itself.

6. Discussion

The results of the study show that the levels of digital economy, environmental regulation and sustainable development generally showed an increasing trend during the study period, but the levels of digital economy and sustainable development have shown a decreasing trend in recent years, and they are still at a lower level compared with the level of environmental regulation, which is different from the results of previous studies [46–48]. What is more, the coupling coordination degree of the three subsystems had a large difference in spatial and temporal distribution. From the trend of temporal changes, the coupling coordination degree of the whole country and the four regions was fluctuating and increasing, with the coupling coordination degree of the eastern region leading, while the rest of the regions were lower than the national average, but the coupling coordination degree of the western region was relatively stable, while the central and northeastern regions fluctuated more. In terms of the spatial distribution pattern, the "Matthew effect" of coupling coordination emerged, with the formation of a "cluster" pattern of high coupling coordination in the middle and upper reaches of the Yangtze River, Shaanxi, Gansu and Ningxia and some provinces and cities in Beijing and Tianjin, and a "chain" pattern of high coupling coordination in the eastern coastal provinces and cities in China. The rest of the region remained at the medium level of coordination. In addition, in terms of global autocorrelation, there was a positive spatial autocorrelation in the degree of coupling and coordination between the digital economy, environmental regulation and sustainable development from a provincial perspective, but it fluctuated up and down from year to year. In terms of local autocorrelation, the spatial distribution of agglomeration types was relatively stable in each year, and the coupling coordination degree of more regions showed a "high–high" and "low–low" spatial agglomeration distribution, among which the "high–high" agglomeration type distribution was more stable in each year. "high–high" agglomeration types were distributed in the eastern coastal areas of China, while "low–low" agglomeration types were more often distributed in the central and western regions.

6.1. Implications of the Study

6.1.1. Theoretical Implications

With regard to the digital economy, environmental regulation and sustainable development, academics have more often discussed the unilateral role of one of these factors on the other. However, as the concept of sustainable development continues to grow, the viewpoint of relying solely on economic factors to explain sustainable development is rather one-sided. Few scholars at home and abroad have integrated the three factors into the same system for analysis and explored the coupling mechanism and mechanism of action among the factors, and the evaluation of each factor often uses a single indicator. In this study, on the basis of combing a large amount of the literature and combining the research results of previous scholars, the output, penetration rate, number of employees and users of the Internet as well as the Digital Inclusive Finance Index of Peking University were used to evaluate the digital economy, the quantity of three waste emissions from industry was assessed from the perspective of environmental regulation costs and finally the evaluation indicators of sustainable development level were determined from three aspects: economic, ecological and social. At the same time, in order to reduce the influence of subjective evaluation factors, the entropy value method was able to objectively assign weights to the levels of the respective systems of the digital economy, environmental regulation and sustainable development, and innovatively incorporated the three into a coupled and coordinated system, illustrating the importance of the coupling and coordination of the three, and providing a theoretical reference for how to improve the level of coordinated development of each region in China.

6.1.2. Practical Implications

The digital economy relies on the rapid integration of its digital technologies with all areas of society, challenging China's economic development model, industrial structure, employment structure and business trade processes, and providing important support for the development of China's real economy. The emergence of a new business economy is bound to have an impact on ecological and environmental elements, requiring that the economic development model must be within the ecological carrying capacity in order to achieve ultimate sustainable development. This paper evaluates the digital economy, environmental regulation and sustainable development based on the characteristics of China's economic and environmental development. By correctly understanding the dynamic evolution of different regions in China to improve the coupling and coordination of the digital economy, environmental regulation and sustainable development, this paper aims to fully realize the dividends of the digital economy, improve the level of green innovation, optimize the energy structure, promote the rational flow of production factors and provide an opportunity to fully realize the benefits of a digital economy. It is also important to promote the rationalization of the flow of production factors, achieve a harmonious balance between human beings and nature and thus truly adhere to the path of sustainable development.

7. Conclusions

Based on the panel data of 30 provinces (autonomous regions and municipalities directly under the central government) in China from 2011 to 2020, this article illustrates the dynamic evolution of each system by constructing an evaluation index system for the digital economy, environmental regulation and sustainable development, and combines the coupling coordination degree model to measure the coupling coordination degree between the three subsystems of digital economy, environmental regulation and sustainable development, revealing the evolution characteristics at the time and space levels.

Therefore, analyzing the trends in the evolution of the coupling and coordination of the digital economy, environmental regulation and sustainable development, the following suggestions can be made:

First, from the perspective of the digital economy, infrastructure is a prerequisite for the sustainable development of the digital economy. Due to its unique location advantage, the eastern region has enjoyed China's "digital economy dividend" earlier, and should pay attention to the improvement of capital utilization efficiency and inter-regional technology sharing in its later development to break the information barrier. In contrast, China's central and western regions have weak economic and technical skills, and need to accelerate the construction of infrastructure, train digital economic talents and guide enterprises in technological innovation in order to lay the foundation for the increase in the scale of digital economic activities.

Secondly, from the perspective of environmental regulation, the factor-input-driven economic growth model has created a structural imbalance in the process of China's economic development. Whether or not a mutually compatible development mechanism can be sought for the economy and the environment has also become the basis for implementing the concept of green development and consolidating the construction of an ecological civilization. Due to the heterogeneity of each region's economic base and factor endowment, as well as the cost of energy conservation and emission reduction, a simple "one-size-fits-all" policy is not universally applicable to regional economic development, and there are even "economic weeds" and "economic crops" to be harvested together. In particular, the central and western regions need to improve the traditional sloppy economic development model and formulate strict environmental regulation policies [49].

Thirdly, from the perspective of sustainable development, sustained and healthy economic growth is a prerequisite for achieving sustainable development, while ecological and environmental improvement and the effective use of resources are the basis for achieving sustainable development. Regions should scientifically assess the ecological and environmental problems they are currently facing and use digital technologies such as artificial intelligence and cloud computing as important tools to precisely implement environmental regulation measures in order to reduce resistance to economic development transformation and promote the unification of ecological, economic and social benefits.

8. Limitations and Prospects

This paper empirically investigates the spatial and temporal distribution of the coupled coordination degree of digital economy, environmental regulation and sustainable development, but due to the lack of data in some regions, it mainly examines from a macro-level provincial perspective and lacks analysis from a micro-level county and municipal perspective. In addition, the evaluation indicators of each system of coupling coordination degree need to continue to be improved in the follow-up study in order to enhance the credibility of the study. Finally, the relationship between the digital economy, environmental regulation and sustainable development can be considered from the perspective of the threshold effect in the follow-up study, hoping to improve the level of synergistic development of each subsystem.

Author Contributions: Y.C.: writing—original draft. J.Y.: conceived and designed the study, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by "Funding of Anhui Province for Social Science Research Project, grant number AHSKY2021D16".

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available upon reasonable request from the authors.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kharrazi, A.; Qin, H.; Zhang, Y. Urban Big Data and Sustainable Development Goals: Challenges and Opportunities. *Sustainability* **2016**, *8*, 1293. [CrossRef]
2. Li, L.; Lei, Y.; Pan, D. Study of CO_2 Emissions in China's Iron and Steel Industry Based on Economic Input–Output Life Cycle Assessment. *Nat. Hazards* **2015**, *81*, 957–970. [CrossRef]
3. Wu, Y. A Model-Driven Analysis of the Relationship between Innovation and Growth in a Green Low-Carbon Economy Based on Open Public Data. *Wirel. Commun. Mob. Comput.* **2022**, *2022*, 1553726. [CrossRef]
4. Pan, H.; Yang, J.; Zhou, H.; Zheng, X.; Hu, F. Global Value Chain Embeddedness, Digital Economy and Green Innovation—Evidence from Provincial-Level Regions in China. *Front. Environ. Sci.* **2022**, *10*, 1027130. [CrossRef]
5. Fan, Y.; Long, S.; Zhang, R.; Ge, C.; Zhang, Y.; Zhang, Q. Effect Evaluation of Eco-Environmental Big Data Resource Integration and Data Sharing Construction. *Wirel. Commun. Mob. Comput.* **2022**, *2022*, 5496629. [CrossRef]
6. Huang, J.; Du, D.; Hao, Y. The Driving Forces of the Change in China's Energy Intensity: An Empirical Research Using DEA-Malmquist and Spatial Panel Estimations. *Econ. Model.* **2017**, *65*, 41–50. [CrossRef]
7. Ding, C.; Liu, C.; Zheng, C.; Li, F. Digital Economy, Technological Innovation and High-Quality Economic Development: Based on Spatial Effect and Mediation Effect. *Sustainability* **2021**, *14*, 216. [CrossRef]
8. Zhang, W.; Zhao, S.; Wan, X.; Yao, Y. Study on the Effect of Digital Economy on High-Quality Economic Development in China. *PLoS ONE* **2021**, *16*, e0257365. [CrossRef]
9. Feng, S.; Chen, K. Impact of Environmental Information Disclosure Policy and Trade on Chinese Paper Industry Environmental Effects. *Int. J. Environ. Res. Public Health* **2022**, *19*, 11614. [CrossRef]
10. Li, G.H.; Zhou, X.L. Can Promoting the Digital Economy Improve Environmental Pollution in China: A Quasi-Natural Experiment Based on the 'Broadband China' Strategy. *Macroeconomics* **2021**, *7*, 146–160.
11. Hampton, S.; Strasser, C.; Tewksbury, J.; Gram, W.; Budden, A.; Batcheller, A.; Duke, C.; Porter, J. Big Data and the Future of Ecology. *Front. Ecol. Environ.* **2013**, *11*, 156–162. [CrossRef]
12. Liu, W.L.; Wang, Y.B. Effect and Mechanism of Digital Economy Empowering Urban Green and High-Quality Development. *South China J. Econ.* **2022**, *8*, 73–91.
13. Bolla, R.; Bruschi, R.; Davoli, F.; Cucchietti, F. Energy Efficiency in the Future Internet: A Survey of Existing Approaches and Trends in Energy-Aware Fixed Network Infrastructures. *IEEE Commun. Surv. Tutorials* **2011**, *13*, 223–244. [CrossRef]
14. Li, R.; Rao, J.; Wan, L. The Digital Economy, Enterprise Digital Transformation, and Enterprise Innovation. *Manag. Decis. Econ.* **2022**, *43*, 2875–2886. [CrossRef]
15. Xie, K.; Xia, Z.H.; Xiao, J.H. The Enterprise Realization Mechanism of Big Data Becoming a Real Production Factor: From the Product Innovation Perspective. *China Ind. Econ.* **2020**, *5*, 42–60.
16. Bruntland, G. Our Common Future: UN World Commission on Environment and Development. *Environment* **1987**, *29*, 25–29.
17. Roostaie, S.; Nawari, N.; Kibert, C. Sustainability and Resilience: A Review of Definitions, Relationships, and Their Integration into a Combined Building Assessment Framework. *Build. Environ.* **2019**, *154*, 132–144. [CrossRef]
18. Wang, C.; Zhan, J.; Xin, Z. Comparative Analysis of Urban Ecological Management Models Incorporating Low-Carbon Transformation. *Technol. Forecast. Soc. Chang.* **2020**, *159*, 120190. [CrossRef]
19. Bilgen, S.; Sarıkaya, I. Contribution of Efficient Energy Use on Economy, Environment, and Sustainability. *Energy Sources Part B Econ. Plan. Policy* **2016**, *11*, 1166–1172. [CrossRef]
20. Vos, R. Defining Sustainability: A Conceptual Orientation. *J. Chem. Technol. Biotechnol.* **2007**, *82*, 334–339. [CrossRef]

21. Zhou, L.; Zhou, C.; Che, L.; Wang, B. Spatio-Temporal Evolution and Influencing Factors of Urban Green Development Efficiency in China. *J. Geogr. Sci.* **2020**, *30*, 724–742. [CrossRef]
22. Wang, L.; Chen, L.; Li, Y. Digital Economy and Urban Low-Carbon Sustainable Development: The Role of Innovation Factor Mobility in China. *Environ. Sci. Pollut. Res.* **2022**, *29*, 48539–48557. [CrossRef] [PubMed]
23. Nambisan, S.; Wright, M.; Feldman, M. The Digital Transformation of Innovation and Entrepreneurship: Progress, Challenges and Key Themes. *Res. Policy* **2019**, *48*, 103773. [CrossRef]
24. Tang, L.; Lu, B.; Tian, T. Spatial Correlation Network and Regional Differences for the Development of Digital Economy in China. *Entropy* **2021**, *23*, 1575. [CrossRef] [PubMed]
25. Raff, Z.; Earnhart, D. The Effect of Environmental Enforcement on Labor: Environmental Workers and Production Workers. *J. Regul. Econ.* **2020**, *57*, 118–133. [CrossRef]
26. Jing, W.J.; Sun, B.W. Digital Economy Promotes High-Quality Economic Development: A Theoretical Analysis Framework. *Economist* **2019**, *2*, 66–73.
27. Zhou, S.F.; Chen, Y.H. Research on the Impact of Digital Economy on High-Quality Economic Development—From the Perspective of Service Industry Structure Upgrading. *J. Ind. Technol. Econ.* **2022**, *41*, 111–121.
28. Yin, S.; Zhang, N.; Ullah, K.; Gao, S. Enhancing Digital Innovation for the Sustainable Transformation of Manufacturing Industry: A Pressure-State-Response System Framework to Perceptions of Digital Green Innovation and Its Performance for Green and Intelligent Manufacturing. *Systems* **2022**, *10*, 72. [CrossRef]
29. Chen, S.R.; Chen, C.Z.; Chen, Y.H.; Wen, X.M.; Sun, Y. Research on the Digital Transformation of Ecological and Environmental Monitoring Oriented to the Modernization of Ecological and Environmental Governance. *Environ. Prot.* **2022**, *50*, 9–12.
30. Chen, T.; Chen, G.; Chen, P.Y. Digital Transformation in China: Development History, Operation Mechanism and Prospect. *Forum Sci. Technol. China* **2022**, *1*, 139–149.
31. Zhou, G.; Zhu, J.; Luo, S. The Impact of Fintech Innovation on Green Growth in China: Mediating Effect of Green Finance. *Ecol. Econ.* **2022**, *193*, 107308. [CrossRef]
32. Chen, H.; Yang, Y.; Yang, M.; Huang, H. The Impact of Environmental Regulation on China's Industrial Green Development and Its Heterogeneity. *Front. Ecol. Evol.* **2022**, *10*, 967550. [CrossRef]
33. Lanz, B.; Wurlod, J.; Panzone, L.; Swanson, T. The Behavioral Effect of Pigovian Regulation: Evidence from a Field Experiment. *J. Environ. Econ. Manag.* **2018**, *87*, 190–205. [CrossRef]
34. Dong, F.; Pan, Y.; Zhang, X.; Sun, Z. How to Evaluate Provincial Ecological Civilization Construction? The Case of Jiangsu Province, China. *Int. J. Environ. Res. Public Health* **2020**, *17*, 5334. [CrossRef]
35. Rosca, E.; Reedy, J.; Bendul, J. Does Frugal Innovation Enable Sustainable Development? A Systematic Literature Review. *Eur. J. Dev. Res.* **2017**, *30*, 136–157. [CrossRef]
36. Huang, X.R.; Guan, W.H.; Chen, M.X.; Hu, H.Y. Urbanization and Optimization of the Yangtze River Delta Urban Agglomeration. *Sci. Geogr. Sin.* **2021**, *41*, 64–73.
37. Bu, X.N.; Zhao, L.H. Voluntary Environmental Regulations and Enterprise Pollution Emission: Based on the Empirical Test of Government Energy-Saving Procurement Policy. *J. Financ. Econ.* **2022**, *48*, 49–63.
38. Li, D.S.; Gou, C.Y. The Impact of Environmental Regulation on Water Resource Utilization Efficiency in the Western China Based on the Heterogeneity of Industrial Sectors and Resource Dependence Perspectives. *Sci. Geogr. Sin.* **2021**, *41*, 2203–2212.
39. Tamasiga, P.; Onyeaka, H.; Ouassou, E. Unlocking the Green Economy in African Countries: An Integrated Framework of FinTech as an Enabler of the Transition to Sustainability. *Energies* **2022**, *15*, 8658. [CrossRef]
40. Liu, R.Z.; He, C. Study on the Threshold Effect of Environmental Regulation on Income Inequality of Urban Residents. *China Soft Sci.* **2021**, 41–52.
41. Qiao, B.; Shen, S.H. Study on Mechanism and Effect of Environmental Regulation on Housing Price. *East China Econ. Manag.* **2021**, *35*, 97–105.
42. Yang, S.H.; Tong, M.H.; Zhang, X.Y. Environmental Pollution, Public Health Demand and Economic Development—Based on Regulation Effect and Threshold Effect. *Zhejiang Soc. Sci.* **2020**, *12*, 4–15+156.
43. Zhao, T.; Zhang, Z.; Liang, S. Digital Economy, Entrepreneurship, and High-Quality Economic Development: Empirical Evidence from Urban China. *Manag. World* **2020**, *36*, 65–75.
44. Silverman, B.W. *Density Estimation for Statistics and Data Analysis*, 1st ed.; Chapman and Hall: London, UK, 1986.
45. Weng, G.M.; Tang, Y.B.; Pan, Y.; Mao, Y.Q. Spatiotemporal Evolution and Spatial Difference of Tourism-Ecology-Urbanization Coupling Coordination in Beijing-Tianjin-Hebei Urban Agglomeration. *Econ. Geogr.* **2021**, *41*, 196–204.
46. Kong, L.; Li, J. Digital Economy Development and Green Economic Efficiency: Evidence from Province-Level Empirical Data in China. *Sustainability* **2022**, *15*, 3. [CrossRef]
47. Luo, R.; Zhou, N. Dynamic Evolution, Spatial Differences, and Driving Factors of China's Provincial Digital Economy. *Sustainability* **2022**, *14*, 9376. [CrossRef]

48. Zhang, S.; Ma, X.; Cui, Q. Statistical Test on the Interaction Between Sustainable Development, Digital Economy and Economic Resilience. *Stat. Decis.* **2023**, *5*, 92–97.
49. Song, X.; Tian, Z.; Ding, C.; Liu, C.; Wang, W.; Zhao, R.; Xing, Y. Digital Economy, Environmental Regulation, and Ecological Well-Being Performance: A Provincial Panel Data Analysis from China. *Int. J. Environ. Res. Public Health* **2022**, *19*, 11801. [CrossRef]