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Addressing the Sustainability Challenges: Digital Economy Information Security Risk Assessment

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Abstract

In the digital economy, sustainable development is based on digital technologies. However, information security issues arising from its use pose significant challenges to sustainable development. Assessing information security risks in the digital economy is crucial for sustainable development. This paper constructs an information security risk assessment indicator system for the digital economy based on information ecology theory. Using game theory to combine CRITIC weights and entropy weights, the information security risk values for the digital economy in 29 provinces of China from 2019 to 2021 are calculated. Quantitative analysis is conducted using Ward's method and the obstacle degree model. The combined weighting results indicate that the information security risks of the digital economy are mostly influenced by information infrastructure. Additionally, the spatio–temporal evolution pattern shows that the risk values of provinces vary to different degrees over time, with a distribution pattern of southern regions > northern regions > northwestern regions. Furthermore, the clustering results indicate that information technology is the primary cause of risk gaps. Finally, the obstacle degree model indicates that digital criminal behavior is the greatest obstacle to information security in the digital economy. The research findings hold significant implications for addressing information security challenges in the global digital economy's sustainable development process, particularly in terms of the replicability of the research methodology and the valuable case study of China.

Keywords: sustainability; digital economy; information security; risk assessment



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1. Introduction

The digital economy is a key driving force behind economic restructuring and promoting high–quality, sustainable economic development. It is reshaping the global economic landscape. The digital economy plays a vital role in fostering technological innovation [1] and mitigating environmental pollution [2] and is a significant force for achieving the United Nations Sustainable Development Goals (SDGs). The China Academy of Information and Communications Technology's "2023 Global Digital Economy White Paper" states that the combined GDP of 51 nations' digital economies in 2022 was USD 41.4 trillion, or 46.1% of their total GDP. This implies that the digital economy is now a vital pillar of economic growth in nations all over the world.

However, with the deep integration of data elements into the social economy, the digital economy faces numerous threats. Information is a vital component of the digital economy, and information security in the digital economy has become a serious challenge facing the world [3]. According to the international standard ISO/IEC 27002, information

security is the protection of protected information against accidental destruction, loss, alteration, disclosure, or unauthorized access during transmission, storage, and processing [4]. Common information security issues in the digital economy are privacy breaches and infrastructure damage. For example, on 4 October 2021, Facebook experienced a DNS server outage that disrupted services across multiple platforms for six hours. Experts estimated the global economic loss caused by the outage to be as high as USD 160 million [5]. The sustainable operation of information and communications infrastructure in the digital economy affects the sustainability of national security [6]. Therefore, the governance of digital economy information security is critical for advancing sustainable development. To strike a balance between development and security, the Central Committee of the Communist Party of China and the State Council proposed in their February 2023 "Overall Plan for the Construction of a Digital China" that establishing trustworthy and controllable digital security safeguards is critical for strengthening core digital capabilities. Nearly 100 nations and territories have passed legislation protecting digital economic security to date; the EU's General Data Protection Regulation is one such example.

Information security risks are the root cause of information security issues and a major obstacle to sustainable development. Advancing sustainable development goals critically depends on monitoring and evaluation [7]. Information security risk assessment is a method of describing information security risks that can intuitively reflect the risk status and existing problems of the assessment object. How can information security risks in the digital economy be assessed to better address the challenges of sustainable development in the digital economy? According to the Global Digital Economy 2023 White Paper, China's digital economy is the second largest in the world, and it is an important participant and driver of the global digital economy. At the same time, China is also an important force in promoting global sustainable development; for example, China strives to achieve peak carbon by 2030. Therefore, assessing the information security risk of China's digital economy is of profound significance for the sustainable development of the global digital economy. In light of this, the objective of this study is to calculate the level of information security risks in China's digital economy, reveal its characteristics, propose specific governance pathways for information security issues in the digital economy, and formulate sustainable development strategies.

The following three categories best describe this paper's contributions. First, our research introduces information ecology theory into the construction of a digital economy information security risk indicator system, integrating information security risks across four dimensions: information personnel, information, information technology, and information environment. This provides an information ecology perspective for current digital economy information security research, which lacks theoretical foundations and systematic thinking. Second, this paper uses game theory combination weighting methods to calculate the weights of each evaluation indicator, a method that can find a reasonable balance among multiple weights. This provides an effective method for combining multiple weights in information security risk analysis. Finally, we conducted an in-depth analysis of the information security risk status of the digital economy from three aspects: spatio–temporal evolution patterns, cluster analysis, and obstacle degree analysis. This offers new insights and targeted recommendations for addressing the sustainable development challenges currently facing the digital economy.

2. Literature Review

2.1. Information Security Issues in the Digital Economy and Sustainable Development

The goal of sustainable development is to satisfy current demands while protecting the ability of future generations to satisfy their own [8]. Achieving sustainable development

requires striking a balance between the economic, social, and environmental facets, according to the UN's 2030 Agenda for Sustainable Development [9]. Digital technology is a key enabler of the sustainable development of the digital economy. It primarily contributes to a more sustainable and equitable world through seven key areas: renewable energy and sustainable technologies, data analytics, consumer empowerment and value co-creation, sustainable urbanization, sustainable consumption, responsible business models, and policy interventions [10]. Information processing, transmission, and storage are essential to the usage of digital technology. As a result, the sustainable growth of the digital economy is seriously threatened by information security concerns. The following section will focus on the impact of information security issues on the sustainable growth of the digital economy, taking into account information availability, confidentiality, and integrity.

The leakage of consumers' personal information can lead to trust deficit issues, which in turn can weaken their willingness to engage in sustainable practices in the digital economy [10]. Inaccurate or unreliable information can lead to mistakes in sustainable development decision-making, such as inaccurate monitoring and tracking of a company's environmental impact [10,11]. Attacks such as denial-of-service (DDoS) interrupt the delivery of digital economy services by disrupting information availability, which not only undermines trust but also increases e-waste, which is not conducive to sustainable development [12]. Therefore, existing research has recognized that addressing information security issues in the digital economy is beneficial for sustainable development; however, it has not specifically addressed how to address these issues.

2.2. Information Security Risks in the Digital Economy

An effective approach to addressing information security issues is to identify existing risks. Information security risk refers to the likelihood of specific threats exploiting asset vulnerabilities and the resulting damage [13]. Assets in the digital economy are primarily presented in the form of data [14], so information security risks mainly target data vulnerabilities and damage. Existing research on cybersecurity risks in the digital economy is primarily theoretical and can be summarized as follows. In the face of complex and changing data information resources, unreliable non–cash payment security systems, irregular information, and digital space legal frameworks, as well as incomplete commercial information confidentiality legal systems, all pose risks to information security [15]. The information infrastructure carries a large amount of essential data, and its destruction threatens information security, affecting the sustainable development of the digital economy [16]. Information security vulnerabilities can compromise the diversity, integrity, and confidentiality of user information, as well as the integrity of technical information, thereby increasing information security risks in the digital economy [17]. Cross–border data flows require clarification of data sovereignty. Ambiguity in data jurisdiction and governance rights, as well as asymmetrical data governance capabilities, will pose threats to information security [18].

In general, first, current research has identified digital economy information security risks from specific perspectives, but there has been little attention paid to constructing a digital economy information risk factor indicator system from a holistic and systematic perspective. Second, existing research remains at the theoretical analysis level and has not conducted in–depth research on issues such as critical information security risks, spatio–temporal evolution patterns, and obstacles to information security. Therefore, it has not been able to put forward targeted sustainable development recommendations.

2.3. Information Security Risk Analysis

Information security risks are formed by the intertwining of various complex factors in the system. The right models and technical measurements must be used in order to evaluate the risks and meet risk management goals. Risk identification, risk analysis, and risk evaluation are the three main parts of information security risk assessment. Among them, risk analysis can be divided into qualitative risk analysis, quantitative risk analysis, and semi-quantitative analysis [13]. Quantitative analysis methods can provide more objective and accurate analysis results and are commonly used risk analysis methods. The key to quantifying risk lies in reasonably weighing risk evaluation indicators. Common subjective weighting methods include AHP [19], DEMATEL [20], etc. Objective weighting methods include the CRITIC method [21], the entropy weight method [22], the coefficient of variation method [23], etc. Objective weighting is a method of assigning weights based on the patterns of the data itself, which can effectively avoid the interference of subjectivity in the results. Combining weights obtained from different methods can yield more reasonable results. However, previous studies have primarily used the multiplication synthesis method [21,22], which is relatively simple but prone to significant deviations when weight distributions are uneven.

Based on existing research, this paper constructs an information security risk assessment index system for the digital economy based on information ecology theory, and assesses information security risks in the digital economy from a relatively systematic and comprehensive perspective. At the same time, the CRITIC–entropy weight–game theory method (CRITIC–EWM–GT) is used to calculate the information security risk value of the digital economy. Subsequently, Ward's method and the obstacle degree model are used to analyze the risk situation. This provides a reference basis for better responding to the challenges of sustainable development in the digital economy.

3. Theoretical Analysis and Research Methods

3.1. Theoretical Analysis

The governance of digital economy information security issues cannot be approached solely from a technical perspective, as people drive the development of the digital economy. At the same time, digital economy information security risks are composed of multiple factors, including digital system, information infrastructure, and information security vulnerabilities, forming a complex system. Therefore, digital economy information security risks must be identified from a systemic perspective. Information ecology theory provides a highly applicable framework for analyzing information security issues [24].

Information ecology was first proposed in the 1960s. It is a set of theories that reflect the connection between ecological thinking and the digital-information environment [25]. Nardi and O'Day believe that information ecosystems are complex systems composed of people, work, values, and technology in specific environments [26]. Many scholars believe that information personnel, information, information technology, and information environment are the four basic elements that constitute an information ecosystem [27,28]. In information ecology theory, the information personnel is the main subject that leads the entire process of information activities; the information is an object that is not subject to human will; the information technology is the medium for information transmission; the information environment is the field where the subject and object interact [28].

In the context of the digital economy, information professionals are the main actors in digital economic activities such as digital products and digital services. Information refers to all information that exists in digital economic activities, including data, information products, etc. Information technology refers to technologies that support the development of the digital economy, such as information and communication technology and big data

analysis technology. The information environment includes the internal environment, such as the digital economy system and the rule of law, and the external environment, such as the digital economy's social and cultural environment. These elements interact with each other through information flows, collectively forming an information ecosystem. Therefore, based on information ecology theory, this study uses information personnel, information, information technology, and the information environment as primary indicators.

Based on a thorough review of relevant research, the primary indicators are scientifically refined to produce 12 secondary indicators:

From an information personnel perspective, information security awareness and digital criminal behavior can pose information security risks to the digital economy. A lack of information security awareness is detrimental to establishing proper security procedures and principles, thereby leading to information security risks related to users [29]. Digital crimes threaten information security through online fraud, malware attacks, and other means. Their digital objects are mainly manifested in areas such as digital financial assets [30].

From an information perspective, false information, the scale of data resources, and information security services pose information security risks to the digital economy. False information is information that is intentionally misleading and intended to cause harm [31]. Malicious brushing and other behaviors in digital economic activities generate false information that disrupts market order and poses information security risks. The expansion of data resources has brought about difficulties in data management and storage, making it easier for information security risks such as unauthorized access, data leakage, and privacy breaches to occur [32].

From an information technology perspective, information infrastructure, digital innovation capabilities, and security protection capabilities pose information security risks to the digital economy. Information infrastructure is the foundation for the development of the digital economy. However, as information infrastructure becomes increasingly sophisticated, it also expands the attack surface and exacerbates information security risks [33]. The development of the digital economy has intensified technological dependence. A lack of independent innovation capabilities often makes it easier to fall victim to cyberattacks, thereby increasing information security risks [34]. Security protection capabilities include application hardening, vulnerability detection, etc. The higher the security protection capabilities, the more helpful it is in discovering and fixing potential information security issues [35,36]. Information security services are information activities that protect information security, including patch management, software management, risk management, etc. [37]. The more developed the information security services are, the stronger the information security protection capabilities are, and the lower the information security risks are.

From an information environment perspective, the social credit system, digital economy system, digital rule of law, and level of information dissemination all influence the information security risks of the digital economy. To achieve information security in the digital economy, it is necessary to start from the macro level and strengthen top–level design to guide the development of the digital economy [38]. The social credit system helps build a safer digital economy credit environment by improving financial credit ratings, strengthening market supervision, and optimizing social governance [39,40]. Digital economy system can effectively enhance the ability to detect information security risks by establishing cybersecurity safeguards [41]. Digital rule of law can effectively prevent risks such as data leakage, tampering, and destruction. A higher level of digital rule of law helps build a sound digital ecosystem, create a safer digital economic information environment, and reduce the occurrence of information security incidents [42]. Information

security awareness campaigns primarily influence information security risks by impacting individuals' awareness of information security [43]. In other words, high–level information security awareness campaigns can enhance personal information security awareness, thereby reducing information security risks in the digital economy.

Based on the quantitative indicators selected by referring to Refs. [44–46], and in accordance with the principles of data availability and quantifiability, this study develops 18 quantitative indicators and establishes a digital economy information security risk assessment indicator system. The indicator framework is shown in Figure 1, and Table 1 presents the data sources and attributes of the indicators.

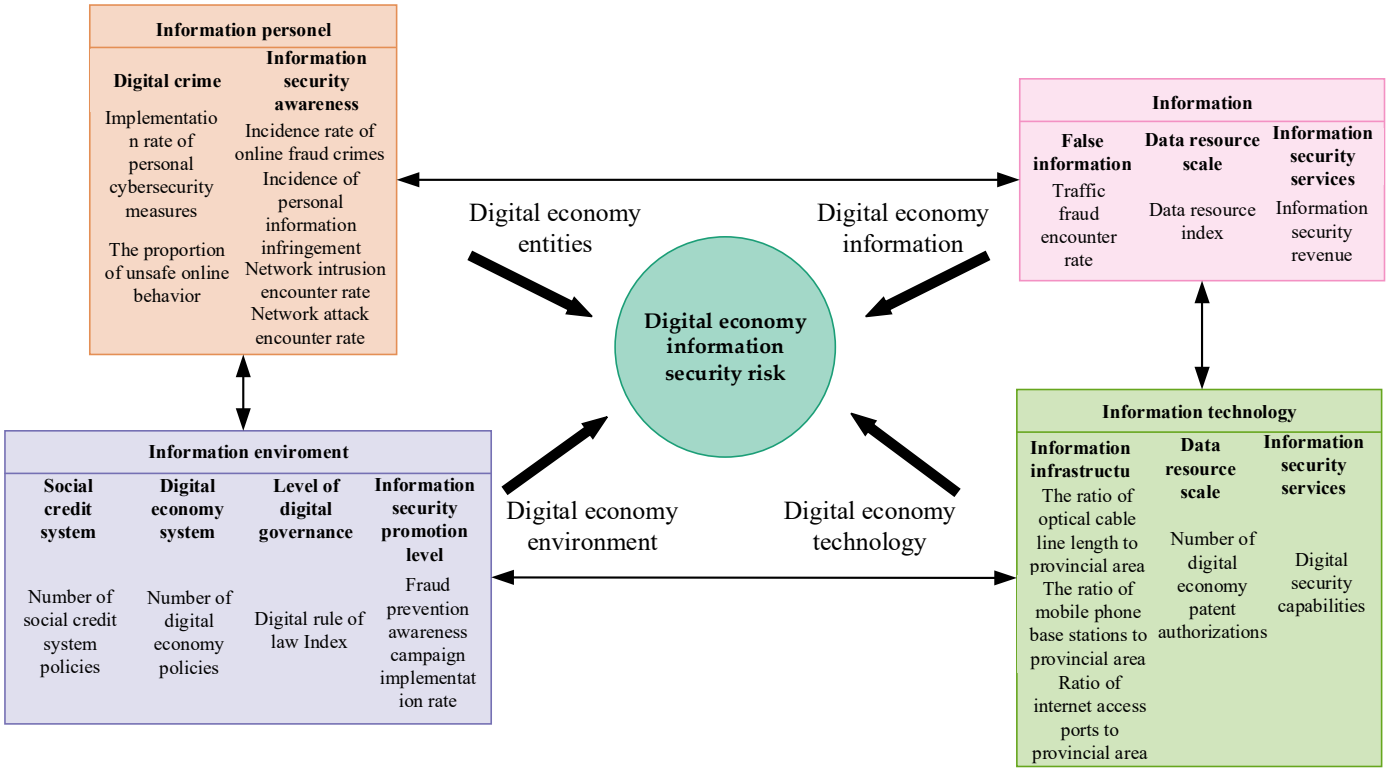


Figure 1. Digital economy information security risk assessment indicator framework.

Table 1. Digital economy information security risk assessment indicator system.

Primary Indicators	Secondary Indicators	Quantitative Indicators	Data Sources	Indicator Attributes
Information personnel A	Information security awareness A1	Implementation rate of personal cybersecurity measures A11	Survey report on Chinese netizens' satisfaction with cybersecurity	Negative
		The proportion of unsafe online behavior A12		Positive
	Digital crime A2	Incidence rate of online fraud crimes A21	Survey report on Chinese netizens' satisfaction with cybersecurity	Positive
		Incidence of personal information infringement A22		Positive
Information personnel A	Digital crime A2	Network intrusion encounter rate A23	Survey report on Chinese netizens' satisfaction with cybersecurity	Positive
		Network attack encounter rate A24		Positive

Table 1. *Cont.*

Primary Indicators	Secondary Indicators	Quantitative Indicators	Data Sources	Indicator Attributes
Information B	False information B1	Traffic fraud encounter rate B11	Survey report on Chinese netizens' satisfaction with cybersecurity	Positive
	Data resource scale B2	Data resource index B21	China's big data regional development level assessment white paper	Positive
	Information security services B3	Information security revenue B31	China statistical yearbook	Negative
Information technology C	Information infrastructure C1	The ratio of optical cable line length to provincial area C11	China statistical yearbook	Positive
		The ratio of mobile phone base stations to provincial area C12		Positive
		Ratio of internet access ports to provincial area C13		Positive
	Digital innovation capabilities C2	Number of digital economy patent authorizations C21	Chinese research data services platform	Negative
	Safety protection capabilities C3	Digital security capabilities C31	Report on the innovative development of China's big data	Negative
Information environment D	Social credit system D1	Number of social credit system policies D11	Peking University Law Library	Negative
	Digital economy system D2	Number of digital economy policies D21	Peking University Law Library	Negative
	Level of digital rule of law D3	Digital rule of law index D31	Report on the innovative development of China's big data	Negative
	Information security promotion level D4	Fraud prevention awareness campaign implementation rate D41	Survey report on Chinese netizens' satisfaction with cybersecurity	Negative

Survey report on Chinese netizens' satisfaction with cybersecurity can be accessed at https://www.iscn.org.cn/ (accessed on 4 July 2025).

3.2. Research Methods

Based on the principles of data completeness and accessibility, this study selects panel data from 29 provinces in China from 2019 to 2021 to assess the information security risks of the digital economy.

3.2.1. Min–Max Normalization

Since the units of the quantitative indicators in this paper are different, it is necessary to process the original data to eliminate the influence of different units of measurement on the analysis results. This paper uses the min–max normalization method to perform a linear transformation on the data, mapping the original data to the interval [0, 1].

Positive indicators:

$$y_{ij} = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \quad (1)$$

Negative indicators:

$$y_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \quad (2)$$

where x_{ij} represents the actual value of the jth indicator in the ith object, y_{ij} represents the result of the data processing, i = 1, . . ., m, j = 1, . . ., n.

3.2.2. CRITIC–EMW–GT Weighting

This paper employs a method that combines the CRITIC method and the entropy weight method to calculate the weights of indicators, allowing for a more objective and accurate reflection of these weights. The reason for this is that the entropy weight method can assess the degree of dispersion between indicators, whereas the CRITIC approach can evaluate the intensity of comparison and the degree of conflict between indicators [47].

Calculate the information content C_j of the jth indicator using the CRITIC method:

$$\overline{y}_j = \frac{1}{m}\sum_{i=1}^{m} y_{ij} \tag{3}$$

$$S_j = \sqrt{\frac{\sum_{i=1}^{m} (y_{ij} - \overline{y}_j)^2}{m-1}} \tag{4}$$

$$C_j = S_j \sum_{k=1}^{m} \left(1 - \left|r_{kj}\right|\right) \tag{5}$$

where S_j is the standard deviation of the jth indicator, and r_{kj} is the correlation coefficient between the kth indicator and the jth indicator. The standard deviation reflects the strength of comparison between indicators, while the correlation coefficient reflects the degree of conflict between indicators.

The weight w_{1j} of the jth indicator obtained by the CRITIC method:

$$w_{1j} = \frac{C_j}{\sum_{j=1}^{n} C_j} \tag{6}$$

- The entropy weight method's primary concept is to measure the amount of information entropy in order to determine the degree of dispersion of indicators. The degree of dispersion of the indicators and the influence on the evaluation outcomes increase with decreasing information entropy [48].

  Weight p_{ij} of the jth indicator:

$$p_{ij} = \frac{y_{ij}}{\sum_{i=1}^{m} y_{ij}} \tag{7}$$

  Information entropy e_j of the jth indicator:

$$e_j = -\frac{1}{\ln m}\sum_{i=1}^{m} p_{ij} \ln p_{ij} \tag{8}$$

  The weight w_{2j} of the jth indicator obtained by the entropy weight method:

$$w_{2j} = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)} \tag{9}$$

- Following Refs. [49,50], this paper uses the game theory combination weighting method to determine the weighting coefficients. The game theory weighting method can minimize the sum of the deviations between the combined weights and the individual weights.

The vector w of the combination weights can be expressed as

$$w = \alpha_1 {w_1}^T + \alpha_2 {w_2}^T \tag{10}$$

where α_1 is the CRITIC method coefficient, and α_2 is the entropy weight method coefficient, $w_1 = w_{11}, w_{12}, \ldots, w_{1n}$, $w_2 = w_{21}, w_{22}, \ldots, w_{2n}$.

The objective function that minimizes the deviation between w and w_1 and w_2 is

$$\min \left\| w - {w_p}^T \right\|, \; p = 1, 2 \tag{11}$$

Based on the properties of matrix differentiation, the equivalent system of linear equations of the above equation can be expressed as

$$\begin{bmatrix} w_1 {w_1}^T & w_1 {w_2}^T \\ w_2 {w_1}^T & w_2 {w_2}^T \end{bmatrix} \begin{bmatrix} \alpha_1 \\ \alpha_2 \end{bmatrix} = \begin{bmatrix} w_1 {w_1}^T \\ w_2 {w_2}^T \end{bmatrix} \tag{12}$$

Considering that weight coefficients may be negative, take the absolute value of the weight coefficients and perform normalization:

$$\begin{aligned} {\alpha_1}^* &= \frac{|\alpha_1|}{|\alpha_1 + \alpha_2|} \\ {\alpha_2}^* &= \frac{|\alpha_2|}{|\alpha_1 + \alpha_2|} \end{aligned} \tag{13}$$

where ${\alpha_1}^*$ is the normalized CRITIC method coefficient, and ${\alpha_2}^*$ is the normalized entropy weight method coefficient.

Finally, the combination weight W_j of the jth indicator can be obtained:

$$W_j = {\alpha_1}^* w_{1j} + {\alpha_2}^* w_{2j} \tag{14}$$

- The risk rating value R_i of the ith research subject is

$$R_i = \sum_{j=1}^{n} W_j y_{ij} \tag{15}$$

3.2.3. Ward's Method

The Ward's method is a hierarchical clustering algorithm. This method first treats all samples as separate categories, then merges categories to form new ones, combining the two categories with the smallest sum of squared deviations until all samples are grouped into a single category [51]. The Ward's method can minimize intra-class differences while maximizing inter-class differences, and has strong clustering capabilities. If categories a and b are merged, the increase in the sum of squared deviations L(a,b) is

$$L(a, b) = \frac{n_a n_b}{n_a + n_b} \| c_a - c_b \|^2 \tag{16}$$

where n_a is the number of samples in category a, and n_b is the number of samples in category b, c_a is the center point of category a, and c_b is the center point of category b.

3.2.4. Obstacle Degree Model

The obstacle degree model measures the degree of obstacles to the development of indicators based on the contribution of factors and the deviation of indicators [52]. In this paper, factor contribution is represented by indicator weights, and indicator deviation is replaced by normalized sample data.

The obstacle degree O_{ij} of the jth indicator of the ith object:

$$O_{ij} = \frac{W_j \times y_{ij}}{\sum_{j=1}^{n} W_j \times y_{ij}} \times 100\% \quad (17)$$

4. Results and Discussion

4.1. CRITIC–EWM–GT Weight

The weighting of indicators for digital economy information security risk assessment is shown in Table 2.

Table 2. Weights of evaluation indicators.

Quantitative Indicators	CRITIC Weight	Entropy Weight	Combined Weight
A11	0.0634	0.0430	0.0462
A12	0.0614	0.0358	0.0398
A21	0.0575	0.0468	0.0485
A22	0.0550	0.0263	0.0308
A23	0.0552	0.0239	0.0288
A24	0.0659	0.0325	0.0377
B11	0.0611	0.0286	0.0336
B21	0.0699	0.1221	0.1140
B31	0.0480	0.0099	0.0159
C11	0.0417	0.1762	0.1552
C12	0.0396	0.1358	0.1208
C13	0.0398	0.1890	0.1657
C21	0.0470	0.0112	0.0168
C31	0.0644	0.0186	0.0258
D11	0.0501	0.0111	0.0172
D21	0.0574	0.0130	0.0199
D31	0.0544	0.0294	0.0333
D41	0.0680	0.0469	0.0502

The data in the table shows that the combined weight of internet bandwidth access port density (C13) is the highest, at 0.1658. In the digital economy, the density of internet bandwidth access ports has the biggest influence on the degree of information security concerns. Furthermore, the density of optical cable connections and mobile phone base stations can have a big impact on how risky information security is in the digital economy.

Therefore, the information security risk of the digital economy is most significantly influenced by the scale of information infrastructure. This may be because digital infrastructure serves as the foundational architecture of the digital economy, and its security status dictates the evolution of risks [53]. The digital economy cannot flourish without the construction of information infrastructure; yet, in order to encourage long-term growth, it is critical to continuously monitor the information security risks associated with such expansion.

4.2. Spatio–Temporal Pattern Evolution of Information Security Risks in the Digital Economy

4.2.1. Time Evolution Pattern Analysis

According to Table 3, the digital economy information security risk values and risk rankings of various provinces have undergone significant changes over time. Figure 2 provides a more intuitive illustration of this change. Between 2019 and 2021, there were certain differences in the digital economy information security risk values among different

provinces. Shanghai has always been the province with the highest risk of digital economy information security, while Xinjiang has the lowest overall risk. The digital economy information security risk values in Hebei, Shanghai, Zhejiang, Fujian, Shandong, Guangxi, and Guizhou have been increasing year by year, while those in Shanxi, Inner Mongolia, Liaoning, Jiangsu, Jiangxi, Hunan, and Sichuan have been decreasing year by year.

Table 3. Risk value and risk ranking.

Province	2019	Ranking	2020	Ranking	2021	Ranking
Beijing	0.3950	3	0.4786	3	0.4351	2
Tianjin	0.3639	6	0.5153	2	0.4100	3
Hebei	0.2977	21	0.3020	16	0.3243	13
Shanxi	0.3062	19	0.2924	19	0.2723	25
Inner Mongolia	0.2925	22	0.2850	23	0.2384	28
Liaoning	0.3207	14	0.3035	15	0.3017	18
Jilin	0.2909	24	0.2904	22	0.2950	19
Heilongjiang	0.3177	15	0.2765	25	0.2873	23
Shanghai	0.7292	1	0.7888	1	0.8127	1
Jiangsu	0.3787	4	0.3191	12	0.3142	16
Zhejiang	0.3229	13	0.3581	5	0.3863	5
Anhui	0.3451	9	0.2920	20	0.3236	14
Fujian	0.3049	20	0.3065	14	0.3336	12
Jiangxi	0.3375	10	0.3256	10	0.2823	24
Shandong	0.3752	5	0.3768	4	0.3796	6
Henan	0.2917	23	0.2953	18	0.2944	21
Hubei	0.2756	26	0.3369	7	0.2947	20
Hunan	0.3523	8	0.2913	21	0.2883	22
Guangdong	0.4024	2	0.3344	8	0.3376	11
Guangxi	0.3162	16	0.3296	9	0.3617	8
Hainan	0.3619	7	0.3256	10	0.3616	9
Chongqing	0.3269	12	0.3139	13	0.3674	7
Sichuan	0.3326	11	0.3207	11	0.3052	17
Guizhou	0.3135	18	0.3505	6	0.3971	4
Yunnan	0.2827	25	0.2987	17	0.2715	26
Shaanxi	0.3141	17	0.2836	24	0.3438	10
Gansu	0.2684	27	0.2448	27	0.2517	27
Ningxia	0.2532	28	0.2305	28	0.3197	15
Xinjiang	0.2446	29	0.2747	26	0.2291	29

To further analyze the reasons for the year-on-year increase and decrease in risk values, we selected the three provinces with the largest increases (Shanghai, Zhejiang, and Guizhou) and the three provinces with the largest decreases (Jiangsu, Jiangxi, and Hunan) for analysis. As shown in Figure 3, the primary reason for the increase in Shanghai's risk value is the information dimension, specifically the increase in the scale of data resources, which corresponds to the full completion of Shanghai's "big data resource platform". The primary reason for the increase in Zhejiang's risk value is also the information dimension, specifically the significant increase in the scale of digital resources, which corresponds to the completion of several "data highways" in Zhejiang Province. The primary reason for the increase in Guizhou's risk value is the information personnel dimension, specifically the increase in digital criminal activities, which corresponds to the sharp rise in the growth rate of telecommunications network fraud cases in Guizhou.

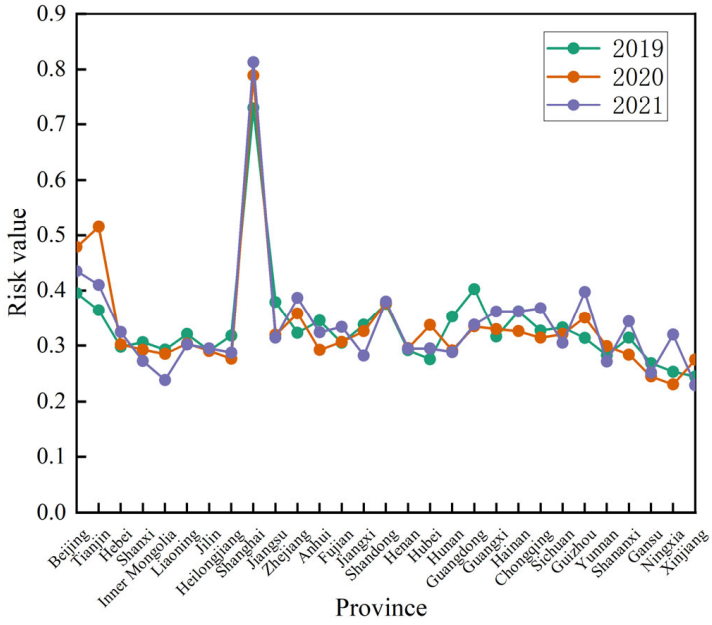


Figure 2. Risk values for different provinces in different years.

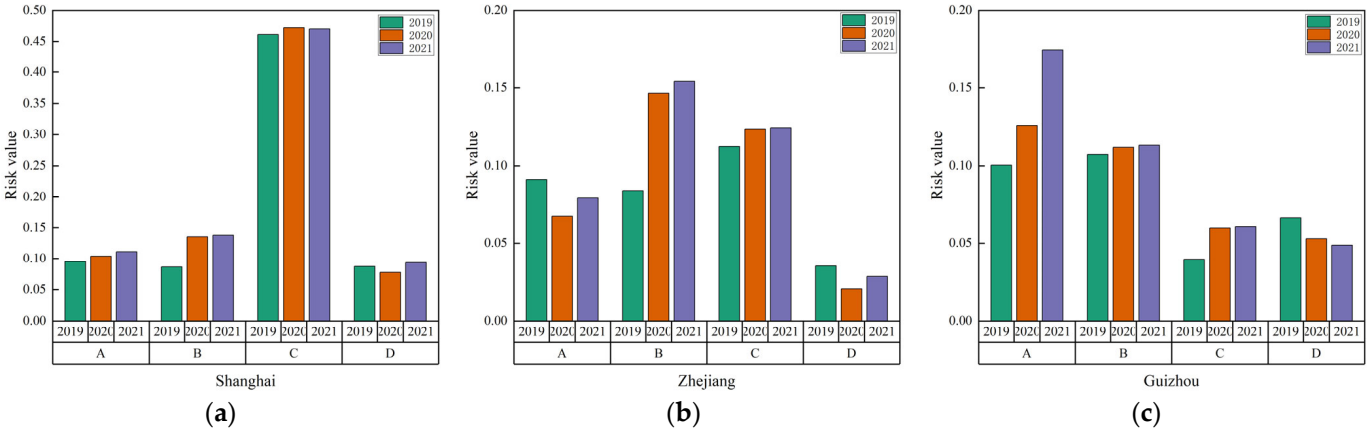
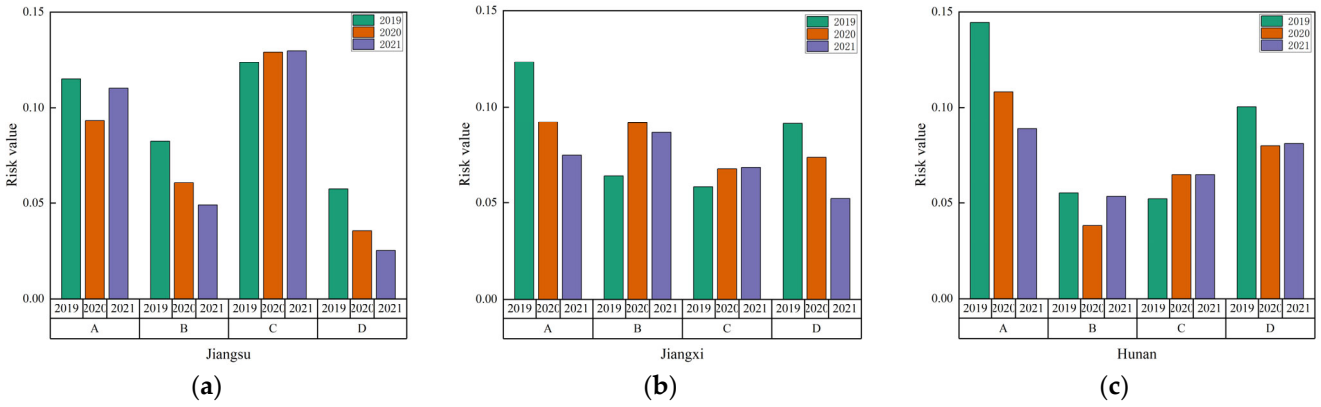


Figure 3. (**a**) Shanghai primary indicator risk values over time; (**b**) Zhejiang primary indicator risk values over time; (**c**) Guizhou primary indicator risk values over time.

As shown in Figure 4, the decrease in Jiangsu's risk value is mainly due to the information dimension and the information environment dimension. Specifically, this is attributed to the reduction in the scale of false information and data resources, as well as the decrease in all secondary indicators under the information environment dimension. The decrease in Jiangxi's risk value is mainly due to the information personnel dimension, specifically the improvement in information security awareness, which corresponds to Jiangsu's ongoing cybersecurity publicity campaigns and educational efforts. The decrease in Hunan's risk value is also mainly due to the information personnel dimension, specifically the improvement in information security awareness and the reduction in digital criminal activities, which corresponds to Hunan's public security authorities' stringent crackdown on telecommunications network fraud and other criminal activities. Although the risk reduction in these three provinces is significant, the overall level of digital economy development is still increasing [54], effectively balancing the development and security of the digital economy.

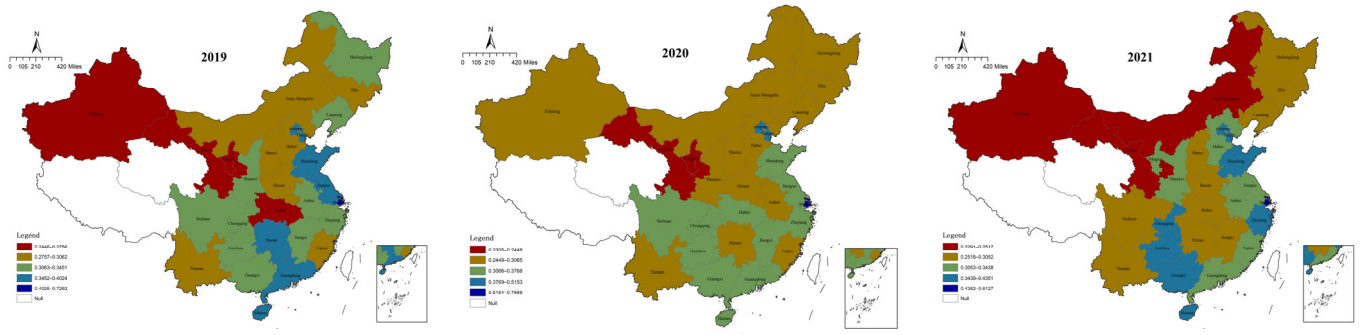


(**a**) (**b**) (**c**)

Figure 4. (**a**) Jiangsu primary indicator risk values over time; (**b**) Jiangxi primary indicator risk values over time; (**c**) Hunan primary indicator risk values over time.

4.2.2. Spatial Evolution Pattern Analysis

Replace actual risk with relative risk and use the natural breakpoint method in ArcGIS 10.8.1 software to classify risk values into five categories: very high, high, medium, low, and very low. Figure 5 intuitively shows the spatial variation in China's digital economy information security risk levels. Overall, the risk values are distributed in the following order: southern region > northern region > northwestern region. This distribution pattern is similar to Ref. [55], where the level of digital economic development in the southern areas is higher than that in northern regions. Therefore, a high level of digital economy development is likely to be accompanied by high information security risk levels, necessitating a focused approach to preventing security issues. The vast majority of provinces are at medium or low risk levels, with high risk levels mainly concentrated in the eastern coastal regions. The risk gap between provinces in 2020 was smaller than in the other two years, possibly due to the COVID-19 pandemic driving digital transformation in the different areas [56].



(**a**) (**b**) (**c**)

Figure 5. (**a**) China's digital economy information security spatial pattern in 2019; (**b**) China's digital economy information security spatial pattern in 2020; (**c**) China's digital economy information security spatial pattern in 2021.

4.3. Classification of Provinces

To analyze the causes of the differences in risk levels across provinces, the average risk values over three years for each province are clustered. IBM SPSS Statistics 26 software is used to perform ward clustering, and Figure 6 displays the clustering results. Based on the clustering results, all provinces are divided into three categories. The overall risk averages and the risk averages of the four primary indicators are calculated for each of the three categories, with the results presented in Table 4. First, there are significant differences in the overall risk averages across different categories. The risk differences in the information per-

sonnel dimension across the three categories are not significant, indicating that information personnel is not the primary cause of the disparities. The information technology dimension is the key factor contributing to the differences in digital economy information security risk values, with the mean value for Category III being significantly higher than that of the other two categories. Category I is information-personnel-information-environment-dominated risk type, Category II is information-personnel-information-technology-dominated risk type, and Category III is information-information-technology-dominated risk type.

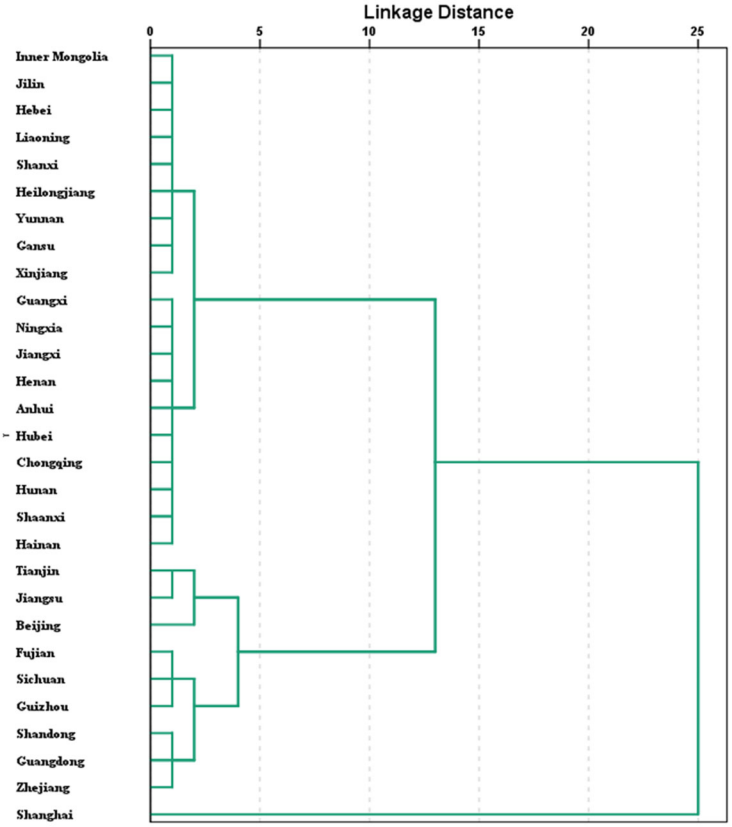


Figure 6. Ward's method results.

Table 4. Mean risk values for different types of provinces.

Type	Province	Mean	Mean of A	Mean of B	Mean of C	Mean of D
I	Inner Mongolia, Jilin, Hebei, Liaoning, Shanxi, Heilongjiang, Yunnan, Gansu, Xinjiang, Guangxi, Ningxia, Jiangxi, Henan, Anhui, Hubei, Chongqing, Hunan, Shaanxi, Hainan	0.2998	0.1075	0.0505	0.0612	0.0806
II	Tianjin, Jiangsu, Beijing, Fujian, Sichuan, Guizhou, Shandong, Guangdong, Zhejiang	0.3647	0.1052	0.1016	0.1044	0.0535
III	Shanghai	0.7768	0.1033	0.1198	0.4678	0.0859

This finding expands the insights of Ref. [10], indicating that disparities in information technology not only lead to the digital divide and uneven development but also result in disparities in digital economy information security risks. Additionally, provinces should implement targeted preventive measures based on their specific risk characteristics to ensure the sustainable development of the digital economy.

4.4. Barriers to Digital Economy Information Security Risks

4.4.1. Overall Obstacle Factors

Calculate the average value of the obstacle scores for all secondary indicators. The top five secondary indicators with the highest scores are identified as the key obstacles constraining the digital economy's information security. The results are shown in Table 5. The average obstacle scores for secondary indicators, from highest to lowest, are as follows: Digital criminal behavior (A2) > Information infrastructure (C1) > Information security awareness (A1) > Data resource scale (B2) > Information security promotion level (D4). Therefore, digital criminal behavior is the largest obstacle to the security of information in the digital economy. This is primarily due to the neglect of data protection, which leads to privacy breaches, and privacy breaches further exacerbate digital criminal behavior [3].

Table 5. Average obstacle degree values for secondary indicators.

A2	C1	A1	B2	D4
21.46%	12.96%	11.52%	10.00%	7.12%

The obstacle score for information security awareness in Figure 7 has been declining year by year, which corresponds to the increasing importance China attaches to information security education and awareness. The degree of obstacles to data resource scales has increased year by year, corresponding to the continuous advancement of China's data opening process. The increase in the scale of open data has brought more information security risks. The degree of obstacles to digital crime and information security awareness has fluctuated downward, while the degree of obstacles to information infrastructure has fluctuated upward. In future digital economy information security management, it is necessary to closely monitor the information security risks posed by digital crimes, while also paying attention to the growing threats to digital economy information security posed by information infrastructure and the scale of data resources, to ensure the sustainable development of the digital economy.

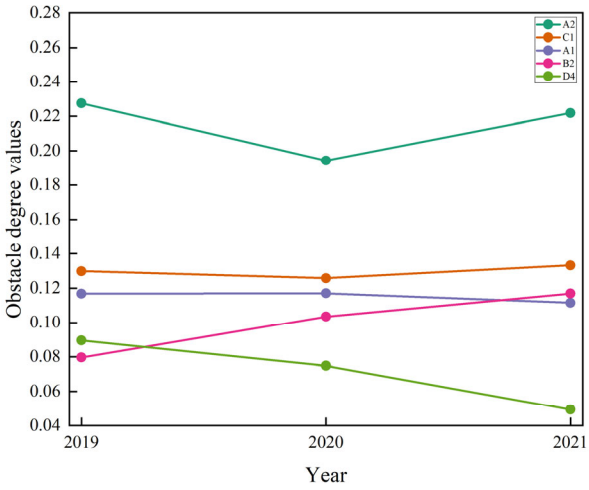


Figure 7. Secondary Indicator Obstacle degree values from 2019 to 2021.

4.4.2. Obstacle Factors in Each Province

The security barriers to the digital economy vary by province, as shown in Table 6. Information Infrastructure (C1) is the top barrier factor for Beijing, Tianjin, Shanghai, and Jiangsu, where the density of information infrastructure as an asset is higher, thereby increasing the potential attack surface. Digital Criminal Behavior (A2) is the primary obstacle factor for Hebei, Shanxi, Inner Mongolia, Liaoning, Jilin, Anhui, Jiangxi, Henan, Hubei, Hunan, Guangxi, Hainan, Chongqing, Sichuan, Yunnan, Shaanxi, Gansu, Ningxia, and Xinjiang, and the encounter rate of digital criminal behavior is relatively high in these provinces, which is the primary factor that brings about information security risk. Information security awareness (A1) is the top obstacle factor for Heilongjiang, which indicates that the citizens of Heilongjiang have low information security awareness, and information security literacy needs to be further improved. Digital resource scale (B2) is the top obstacle factor for Zhejiang, Fujian, Shandong, Guangdong, and Guizhou, and the scale of open data resources in these provinces is large. Therefore, provinces need to carry out targeted risk management and prevention based on their own shortcomings to guarantee the security and sustainable development of the digital economy.

Table 6. Annual obstacle degree values for secondary indicators from 2019 to 2021.

Province	Year	Index Ranking				
		1	2	3	4	5
Beijing	2019	C1(42.97%)	D4(12.05%)	A1(10.46%)	B2(8.27%)	A2(6.32%)
	2020	C1(35.09%)	A2(16.62%)	B2(14.85%)	A1(13.99%)	D4(6.05%)
	2021	C1(38.12%)	B2(19.97%)	A1(11.07%)	A2(10.79%)	D4(5.48%)
Tianjin	2019	C1(35.89%)	A2(13.71%)	A1(11.43%)	B2(7.61%)	D2(5.47%)
	2020	C1(25.84%)	A2(24.49%)	B2(13.76%)	A1(13.55%)	C3(4.64%)
	2021	C1(32.08%)	B2(14.05%)	A1(13.49%)	A2(12.91%)	C3(5.93%)
Hebei	2019	D4(15.75%)	A1(14.49%)	A2(13.49%)	C1(11.58%)	D3(8.19%)
	2020	A2(19.72%)	A1(17.11%)	D4(11.80%)	C1(11.28%)	C3(8.39%)
	2021	A2(21.45%)	A1(14.78%)	C1(10.52%)	D3(8.14%)	C3(7.78%)
Shanxi	2019	A2(30.20%)	A1(13.27%)	D3(8.46%)	D4(8.02%)	C3(7.92%)
	2020	A2(23.14%)	A1(14.03%)	D4(11.22%)	C3(8.73%)	D3(8.28%)
	2021	A2(27.73%)	D3(11.76%)	A1(10.40%)	C3(9.42%)	C1(8.65%)
Inner Mongolia	2019	A2(23.74%)	A1(13.52%)	D4(13.07%)	C3(8.82%)	D3(8.69%)
	2020	A1(18.76%)	A2(16.41%)	D4(16.02%)	C3(8.88%)	B1(8.55%)
	2021	A2(29.77%)	C3(10.73%)	A1(9.83%)	D3(8.86%)	D2(7.91%)
Liaoning	2019	A2(19.22%)	A1(16.37%)	D4(13.91%)	C1(9.98%)	B1(7.58%)
	2020	A2(16.97%)	D4(16.54%)	A1(12.90%)	C1(10.27%)	C3(8.39%)
	2021	A2(23.80%)	A1(17.81%)	C1(10.16%)	C3(8.39%)	D3(7.00%)
Jilin	2019	A2(18.36%)	D4(17.08%)	A1(13.48%)	D3(8.78%)	C3(8.22%)
	2020	A2(18.38%)	A1(16.92%)	D4(16.04%)	C3(8.71%)	B1(6.87%)
	2021	A2(30.85%)	A1(14.43%)	C3(8.56%)	D4(7.43%)	D2(6.66%)
Heilongjiang	2019	A2(21.46%)	A1(13.44%)	D4(12.59%)	D3(9.68%)	B2(9.05%)
	2020	A1(20.24%)	A2(17.85%)	D4(11.80%)	D3(9.55%)	C3(9.04%)
	2021	A1(20.84%)	A2(20.69%)	D4(10.01%)	C3(8.70%)	D3(7.90%)
Shanghai	2019	C1(60.57%)	A1(7.99%)	B2(5.39%)	D4(5.09%)	A2(5.03%)
	2020	C1(56.01%)	B2(11.80%)	A2(7.18%)	A1(5.97%)	D4(3.46%)
	2021	C1(54.35%)	B2(12.41%)	A2(8.08%)	D4(6.18%)	A1(5.60%)
Jiangsu	2019	C1(26.93%)	A2(22.04%)	B2(14.85%)	A1(8.36%)	D4(5.61%)
	2020	C1(31.68%)	A2(22.46%)	B2(11.97%)	C3(7.06%)	A1(6.76%)
	2021	C1(32.32%)	A2(25.22%)	A1(9.87%)	B2(7.65%)	C3(7.21%)

Table 6. *Cont.*

Province	Year	Index Ranking				
		1	2	3	4	5
Zhejiang	2019	C1(29.29%)	A2(17.22%)	B2(14.28%)	A1(11.05%)	B1(7.12%)
	2020	B2(31.83%)	C1(25.54%)	A2(12.90%)	C3(5.96%)	A1(5.93%)
	2021	B2(29.51%)	C1(23.71%)	A2(12.71%)	A1(7.82%)	B1(6.43%)
Anhui	2019	A2(22.25%)	A1(13.53%)	C1(11.87%)	B2(11.22%)	D4(8.11%)
	2020	A2(18.43%)	A1(14.21%)	C1(13.64%)	D4(9.22%)	C3(8.40%)
	2021	A2(27.01%)	C1(12.69%)	A1(8.53%)	D4(7.82%)	C3(7.49%)
Fujian	2019	A2(24.22%)	B2(14.28%)	A1(10.93%)	C1(9.08%)	B1(8.56%)
	2020	B2(24.70%)	C1(12.39%)	A2(11.73%)	A1(10.20%)	C3(7.98%)
	2021	B2(23.40%)	A2(15.02%)	A1(13.56%)	C1(11.57%)	B1(7.96%)
Jiangxi	2019	A1(18.43%)	A2(18.23%)	D4(10.78%)	C1(7.83%)	B1(7.60%)
	2020	B2(16.72%)	A2(15.28%)	A1(13.02%)	C1(8.35%)	C3(7.72%)
	2021	A2(20.10%)	B2(15.30%)	C1(9.88%)	B1(9.74%)	C3(8.88%)
Shandong	2019	B2(28.05%)	C1(15.93%)	A2(15.56%)	A1(7.45%)	D4(7.04%)
	2020	B2(27.66%)	C1(14.97%)	A2(14.18%)	D4(8.68%)	C3(6.16%)
	2021	B2(29.66%)	A2(17.26%)	C1(14.78%)	D4(6.55%)	A1(6.40%)
Henan	2019	A2(27.44%)	C1(13.62%)	A1(10.42%)	B2(8.10%)	D3(7.14%)
	2020	A2(15.85%)	B2(15.20%)	C1(13.16%)	A1(12.44%)	D3(8.89%)
	2021	B2(16.54%)	A2(16.37%)	C1(13.96%)	A1(13.70%)	C3(8.14%)
Hubei	2019	A2(23.58%)	A1(11.62%)	C1(9.71%)	D4(8.88%)	D2(6.80%)
	2020	A2(23.46%)	B2(12.43%)	D4(9.60%)	A1(8.91%)	C1(7.93%)
	2021	A2(18.11%)	D4(11.68%)	A1(10.75%)	C1(9.59%)	C3(7.64%)
Hunan	2019	A2(25.53%)	A1(15.50%)	D4(11.12%)	D3(7.55%)	C1(7.11%)
	2020	A2(24.69%)	A1(12.48%)	C1(8.62%)	C3(8.35%)	D3(7.98%)
	2021	A2(21.83%)	A1(8.95%)	C1(8.95%)	C3(8.20%)	D3(8.07%)
Guangdong	2019	B2(28.33%)	A2(23.03%)	C1(16.41%)	A1(8.61%)	D4(5.05%)
	2020	B2(25.92%)	A2(22.39%)	C1(19.43%)	A1(10.85%)	C3(5.01%)
	2021	B2(26.80%)	A2(22.96%)	C1(19.74%)	A1(10.48%)	C3(4.46%)
Guangxi	2019	A2(32.64%)	A1(12.38%)	D3(9.64%)	B1(8.57%)	D4(8.18%)
	2020	A2(21.49%)	B2(18.30%)	A1(8.61%)	D3(8.56%)	C3(7.72%)
	2021	A2(33.35%)	B2(17.68%)	A1(9.19%)	C3(7.00%)	C1(5.89%)
Hainan	2019	A2(28.50%)	D4(10.70%)	A1(10.04%)	C1(8.61%)	B2(7.74%)
	2020	A2(15.96%)	B2(15.00%)	D4(11.81%)	C1(9.60%)	C3(7.85%)
	2021	C1(26.56%)	A2(13.36%)	B2(9.64%)	D4(8.39%)	C3(6.99%)
Chongqing	2019	A2(25.18%)	C1(13.66%)	D4(11.86%)	A1(11.77%)	B1(8.15%)
	2020	A2(26.49%)	C1(14.05%)	A1(9.67%)	C3(7.96%)	D4(7.96%)
	2021	A2(26.01%)	B2(15.46%)	C1(12.39%)	A1(8.22%)	C3(6.80%)
Sichuan	2019	A2(24.42%)	A1(14.31%)	B2(13.37%)	D4(9.90%)	B1(7.58%)
	2020	B2(23.30%)	A2(15.92%)	A1(12.32%)	C3(7.56%)	D3(6.53%)
	2021	A2(20.04%)	B2(19.33%)	A1(9.65%)	B1(9.40%)	C3(8.00%)
Guizhou	2019	B2(20.37%)	A1(16.90%)	A2(15.15%)	B1(8.79%)	D4(8.44%)
	2020	B2(24.32%)	A1(20.59%)	A2(15.34%)	C3(7.15%)	C1(5.23%)
	2021	A2(30.34%)	B2(18.41%)	A1(13.61%)	C3(6.29%)	B1(6.11%)
Yunnan	2019	A2(42.53%)	D3(7.82%)	A1(7.58%)	C3(7.19%)	D2(6.83%)
	2020	A2(30.70%)	A1(10.70%)	D4(9.65%)	D3(9.28%)	C3(8.43%)
	2021	A2(27.75%)	A1(14.69%)	D3(10.01%)	C3(9.25%)	B1(7.16%)
Shananxi	2019	A2(21.28%)	D4(15.98%)	A1(11.61%)	B1(7.84%)	D3(6.65%)
	2020	A2(18.02%)	D4(14.65%)	A1(12.45%)	B1(9.42%)	C3(8.94%)
	2021	A2(30.26%)	B1(9.77%)	D4(9.65%)	C3(7.34%)	D3(7.30%)

Table 6. *Cont.*

Province	Year	Index Ranking				
		1	**2**	**3**	**4**	**5**
Gansu	2019	A2(34.42%)	A1(10.14%)	C3(8.51%)	D3(8.50%)	B1(7.69%)
	2020	A2(30.05%)	D3(10.91%)	C3(10.48%)	B1(7.88%)	D2(7.84%)
	2021	A2(28.75%)	C3(10.20%)	B2(9.26%)	A1(8.59%)	D3(7.26%)
Ningxia	2019	A2(33.51%)	B2(12.94%)	D3(12.54%)	D2(7.63%)	C2(6.62%)
	2020	A1(16.14%)	B1(12.57%)	D3(12.31%)	C3(11.19%)	A2(9.33%)
	2021	A2(25.72%)	A1(16.54%)	B2(12.97%)	C3(8.07%)	D3(8.06%)
Xinjiang	2019	A2(31.53%)	D3(13.61%)	A1(12.15%)	D2(8.14%)	B1(7.00%)
	2020	A2(38.02%)	B1(12.23%)	D3(12.12%)	C3(9.12%)	D2(6.99%)
	2021	A2(25.18%)	A1(16.45%)	D3(14.53%)	C3(11.02%)	D2(8.46%)

5. Conclusions and Policy Implications

This study establishes a systematic digital economy information security risk assessment indicator system based on information ecology theory. It conducts a quantitative analysis of the digital economy information security risk status of provinces across China from three aspects: spatio–temporal evolution, risk clustering, and risk barrier degree. The research conclusions are as follows: (1) The results of the combined weighting indicate that the quantitative indicators of information infrastructure have the highest weight, indicating that they have the greatest impact on the information security risks of the digital economy. (2) The spatio–temporal evolution pattern shows that the risk values and rankings of the provinces vary to different degrees over time, which mainly depends on the provinces' own policy measures and practices. The risk level decreases in the order of the southern region, the northern region, and the northwestern region. (3) The clustering results indicate that the largest differences in information technology scores exist between different types of provinces, with information technology being the primary cause of risk disparities. (4) The results of the obstacle analysis indicate that digital criminal activities pose the greatest obstacle to information security in the digital economy. The obstacles posed by the scale of data resources and information infrastructure to information security are on the rise, and the primary obstacle factors vary across provinces.

The following policy implications are proposed: (1) Given that information infrastructure has the greatest impact on the level of information security risks in the digital economy, the government should conduct focused monitoring of its security status during the construction of information infrastructure, assess potential security risks, and improve emergency response mechanisms to address the challenges posed by the sustainable development of the digital economy. (2) Given that information technology is the primary cause of regional risk disparities, governments should guard against the uncertain security risks posed by high levels of digitization, while narrowing the digital divide between regions and promoting a more equitable and sustainable digital economy. (3) Given that digital crimes are the biggest obstacle to information security in the digital economy, the government should focus on combating digital crimes, improving law enforcement capabilities, and strengthening law enforcement to better coordinate the development and security of the digital economy. (4) Given the differences in risk levels and primary obstacles among provinces, the government should adopt a tailored approach and carry out targeted governance work based on the actual risk situation in each province.

This study holds significant implications for addressing the challenges of sustainable development in the digital economy; however, it also has certain limitations. First, due to limitations in data acquisition, the time range of the panel data is relatively short and a

little old. In the future, as more relevant research data becomes available, the time range of the study can be expanded to conduct more accurate research. It is also possible to assess and compare the risk of information security in the digital economy in different countries and regions, so as to better promote international cooperation and contribute to sustainable development. Second, the study does not consider the impact of time on key barrier factors. In the future, time attenuation factors can be introduced into the barrier degree model to better align with the dynamic characteristics of the digital economy. Meanwhile, this study focuses on the assessment of historical data, and in the future, research can be conducted on the prediction of information security risks in the digital economy to provide forward-looking recommendations for sustainable development. In addition, this study assesses the information security of the digital economy from the perspective of risk, and in the future, it can be analyzed from the perspective of policy tools to provide a more complete, sustainable path.

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