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EDITED BY
Shikuan Zhao,
Chongqing University, China

REVIEWED BY
Pengzhen Liu,
Jinan University, China
Xue Lei,
Shanghai University, China
Yang Xu,
Xinjiang University, China
Xiaokai Li,
North China University of Water Conservancy and Electric Power, China

*CORRESPONDENCE
Ting Lei,
b2023140200165@stu.swupl.edu.cn

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Maintain ecological security: analyzing the impact of the digital economy on green and low-carbon land utilization

Ting Lei*

School of National Security, Southwest University of Political Science and Law, Chongqing, China

Introduction: Ecological security is an important part of the overall national security outlook. Maintaining ecological security is a fundamental, overall and strategic requirement related to the long-term stability of the country, the sustainable development of the nation and the happiness and well-being of the people. As the fundamental carrier for human survival and development, the utilization mode, intensity and spatial pattern of land directly determine the health, stability and service functions of the ecosystem, and further affect the ecological security of the region and even the world. At present, China's land resources are confronted with multiple challenges such as ecological and environmental constraints. As a key engine for achieving sustainable utilization of land resources, the digital economy provides a systematic solution for the green and low-carbon use of land. The green and low-carbon utilization of land is an important part of maintaining ecological security. This article explores the promoting effect of the digital economy (DE) on the green and low-carbon utilization of land (GUE). The digital economy is an important way to achieve the carbon reduction targets of land and maintain ecological security.

Method: This paper selects panel data from 31 provinces in China from 2011 to 2023 as research samples, and respectively uses the fixed effects model and the quantile model to explore the promoting and heterogeneous effects of the digital economy (DE) on the green and low-carbon utilization of land (GUE). Furthermore, the mediation model is employed to explore the mediating role of entrepreneurial activity and Internet penetration rate in the digital economy and the green and low-carbon utilization of land, aiming to investigate whether the mediating variables can play a promoting role in maintaining ecological security.

Result: First, the direct impact of the digital economy and the green and low-carbon utilization of land has shown a significant promoting effect. Second, the entrepreneurial activity level and the Internet penetration rate play a significant mediating role in the assessment of the impact of the digital economy on the green and low-carbon utilization of land. Thirdly, the digital economy has a significant promoting effect on the green and low-carbon utilization of land in the eastern and western regions of China, but it shows no significant effect in the central region.

Discussion: This article not only enriches the theoretical research on the green and low-carbon utilization of land by the digital economy, but also provides corresponding empirical evidence. To provide more precise theoretical support for improving the land governance system and achieving ecological and environmental security. Government departments should enhance policy coordination and institutional allocation for the digital economy, combine the diffusion of green and low-carbon technologies with ecological compensation mechanisms, optimize the allocation efficiency of land factors and green and low-carbon technologies, promote the green and low-carbon transformation and upgrading of land, and while facilitating the realization of land carbon reduction targets, achieve the coordinated evolution of ecological protection and sustainable utilization of land resources. Only by deeply integrating "digitalization" into "greening" can ecological security be achieved under the premise of ensuring the green and low-carbon utilization of land resources, providing a solid foundation for building a moderately prosperous society and creating a modern model of harmonious coexistence between humans and nature.

KEYWORDS

digital economy, green and low-carbon utilization of land, entrepreneurial activity, internet coverage, national security

1 Introduction

In recent years, the global warming trend has continued to intensify, and extreme climate events have occurred frequently, posing a severe challenge to ecological security and sustainable development. Carbon emission reduction has become the core path to alleviate the climate crisis. Land use, as a key area of carbon emissions, generates nearly a quarter of the global greenhouse gas emissions (Tian et al., 2021). In China, along with the rapid process of urbanization and industrialization, the problem of carbon emissions caused by land development and utilization has become increasingly prominent. There is an urgent need to reconstruct the land use model through technological innovation to balance the goals of economic development and ecological protection. Against this backdrop, China explicitly put forward the strategic goal of "peaking carbon emissions before 2030 and achieving carbon neutrality before 2060" at the 75th session of the United Nations General Assembly, in order to improve agricultural ecological protection, safeguard the ecological red line of land, and ensure the green and high-quality development of agriculture (Ou et al., 2025). Meanwhile, enhancing the green and low-carbon utilization of land, as the core carrier for the optimal allocation of territorial space that integrates the control of ecological protection red lines, the development of carbon sink resources and intelligent monitoring technologies, has become a key approach to achieving the "dual carbon" goals and an important yardstick for measuring the level of regional ecological civilization construction.

Global ecological and environmental performance data warn us that enhancing ecological protection efficiency is an urgent matter, as it directly concerns national ecological security. Against this backdrop, China has prioritized mitigating ecological risks, and as a core natural resource, the way land is utilized profoundly affects the health and resilience of ecosystems. The traditional extensive land use model, especially the excessive development and pollution in the agricultural sector, not only threatens the quality of cultivated land but also becomes an important source of carbon emissions, exacerbating ecological risks (Jiang et al., 2022). The digital economy, with its powerful capabilities in data acquisition, analysis, integration and intelligent decision-making, provides a revolutionary tool for resolving the contradiction between land protection and development and achieving low-carbon, efficient and sustainable land utilization, becoming a key support point for maintaining ecological security: it can precisely monitor and warn, and build a "digital fence" for ecological protection red lines. It can optimize resource allocation and decision-making, and drive the low-carbon utilization of land. It can enhance the quality and resilience of cultivated land and jointly ensure ecological security (Li et al., 2023). It can promote transparency and synergy, strengthen policy implementation and international cooperation. Maintaining ecological security requires a fundamental transformation of land use patterns, moving towards a low-carbon, intensive and sustainable direction (Shi and Liao, 2025). The digital economy is not merely a tool replacement; rather, it has reshaped the paradigm of low-carbon land use by deeply integrating into the entire land management chain, from red line protection, process monitoring to decision-making optimization and quality improvement (Xu, 2025). By combining the rigid constraints of environmental policies with intelligent management, it effectively balances the local development impulse with the long-term ecological protection demands, providing a technological solution for resolving the contradiction between "short-term benefits and permanent protection." Therefore, vigorously developing and deepening the application of digital technology in the land sector is a modern strategic choice for building a more stable ecological security barrier and achieving harmonious coexistence between humans and nature. Empowering the low-carbon utilization of land with digital technology is a key path to strengthening the ecological security defense line.

In conclusion, the marginal contribution of this paper lies in the following: First, it provides theoretical and empirical evidence for the impact of the digital economy and the green and low-carbon utilization of land, offering reference value for developing countries in promoting the green and low-carbon utilization of land through the digital economy. Secondly, by combining the fixed-effect model selected in this paper, the empirical test of the differentiated emission reduction effects among the eastern, central, and western regions not only provides an important basis for precise regional governance but also offers a more accurate perspective for maintaining national ecological security. Thirdly, identify the dual mediating role of entrepreneurial activity and Internet coverage, clarify the direct path of how the digital economy can curb land carbon emissions through entrepreneurial activity and Internet coverage, and provide reference and implementation paths for achieving low-carbon land utilization in the country. Fourth, this article provides corresponding policy suggestions for government departments, offering policy-level assistance for protecting ecological security and national security in the future.

2 Literature review

The digital economy, with digital knowledge and information as key production factors, modern information networks as important carriers, and information and communication bases as efficiency, is a new economic form that enhances efficiency. As the core engine of the new round of technological revolution and industrial transformation, it provides a brand-new paradigm for the low-carbon transformation of land through data element drive (Shi et al., 2025), technology penetration and reconstruction, and system collaborative optimization (Xu et al., 2025b; Raihan and Mainul Bari, 2024). Regarding the mechanism exploration of low-carbon land utilization, the existing research mainly analyzes the core mechanism system at the theoretical level. The first is to define the connotation of low-carbon land utilization. Scholars have summarized the connotation of low-carbon land use as “maximizing land economic and ecological benefits through the lowest carbon emission intensity” (Song et al., 2021; Wang et al., 2022). The second is to analyze the current predicament. Including multi-purpose land use conflicts (Usman and Makhdum, 2021; Zhang and Liu, 2022), Cost Constraints of Digital Technology Application (Huang et al., 2023; Jan et al., 2023; Zhang et al., 2024). Third, explore emission reduction paths, such as building a “monitoring” system empowered by digital technology (Zysman and Nitzberg, 2020; Wang et al., 2023a), Planning (Chen et al., 2023; Li et al., 2024), and evaluating the “Closed-loop Management System.” The digital economy reshapes the logic of low-carbon land use from multiple dimensions, such as spatial compression, efficiency innovation, and circular catalysis. Essentially, it revolutionizes production methods through data, driving land use to shift from scale expansion to quality enhancement, and thereby achieving low-carbon land use and maintaining ecological security.

Regarding the impact on the GUL, existing research mainly focuses on the comprehensive benefits of the DE for the GUL. On the one hand, there is a supportive view, emphasizing that the DE promotes the low-carbon transformation of land through three paths: the first is the optimization of intelligent management and control. It is pointed out that the Internet of Things and big data can achieve dynamic monitoring of land resources (Yu Q. et al., 2023), precisely regulate high-carbon emission links such as agricultural fertilization (Wang et al., 2023b) and industrial energy consumption (Yao et al., 2022), and reduce the carbon emission intensity per unit of land. The second is the virtual substitution effect. It is proposed that measures such as e-commerce platform economy should be adopted to reduce the demand for warehousing land and compress physical space, and to curb the carbon footprint caused by land development (Karwacka et al., 2020; Zhou et al., 2020). The third is green technological innovation. Emphasize the acceleration of the application of digital technology in photovoltaic agriculture and carbon capture technology, and enhance the carbon sink capacity of the land. These studies suggest that the DE provides a technical paradigm for intensive land use under the “dual carbon” goals. On the other hand, there is a critical perspective. The research points out potential risks. First, the expansion of digital infrastructure may intensify the contradiction between “land and energy,” highlighting the sharp increase in data center land occupation and the rise in regional energy consumption demand, partially offsetting the benefits of emission reduction (Huo et al., 2024). Second, it points out that algorithm-driven land allocation may trigger a “digital divide,” such as less developed regions being forced to take over high-carbon industries due to technological deficiencies, leading to regional transfer of land carbon emissions (Shen et al., 2022; Liu et al., 2024; Huang et al., 2025). Furthermore, against the backdrop of the unbalanced development of the DE, there are significant differences in the coverage rate of digital infrastructure and the digital capabilities of various regions, resulting in the phased heterogeneity of the GUL (Shen et al., 2022; Bernini and Galli, 2024; Tang, 2024).

3 Theoretical mechanism

3.1 Direct effect

The DE reshapes the carbon emission pattern of land use through a path driven by data elements, technological infiltration and reconstruction, and system collaborative optimization. As an important catalyst for China’s high-quality economic development, the digital economy has given rise to technological advancements and green innovations, which are crucial measures for achieving green and high-quality agricultural development. Making good use of the advantages of the digital economy is an important link in promoting the green and low-carbon utilization of land. First, the effect of intelligent monitoring and precise control. Digital technologies such as remote sensing, monitoring, and Internet of Things sensors can obtain real-time data on land resource utilization intensity and ecological environment. Through big data analysis, high-carbon emission links such as excessive fertilization and mechanical tillage energy consumption can be accurately identified, and the planting structure, irrigation scheduling, and energy distribution can be dynamically optimized. Promote the GUL per unit (Korherr and Kanbach, 2023; Razzaq et al., 2023). Second, the full-chain low-carbon decision support effect. Relying on artificial intelligence and blockchain technology, a land carbon footprint traceability platform is constructed to achieve full life cycle carbon emission control from land production planning to circulation and consumption. Relying on big data and intelligent algorithms to match land suitability assessment with the layout of low-carbon crops, the blockchain traceability system incentivizes the premium of green certified agricultural products and promotes the transformation of land to a low-energy consumption and high-carbon sink model (Jin et al., 2022). Third, the substitution effect of virtual space on physical resources. Widely apply digital platform economies such as agricultural product e-commerce and remote agricultural services to reduce the logistics and warehousing demands of traditional production and sales links, and lower the expansion of transportation land and related carbon emissions. Meanwhile, green and low-carbon digital technologies are utilized to simulate land development plans, thereby avoiding extensive land use planning with high carbon emissions and suppressing the generation of land carbon emissions from the source (Chuai et al., 2024).

Based on this, this paper proposes: Hypothesis 1 (H1): The DE can significantly promote GUL.

3.2 Indirect effect

Entrepreneurship and the Internet, as crucial factors in the development of the DE, have always been regarded as important supports for achieving technological innovation and improvement, and also as an important part of alleviating the land environment. With the continuous improvement of the entrepreneurship level and digital infrastructure level in our country, the efficiency of land use has been greatly enhanced. By optimizing the density and spatial layout of land factor input, the entrepreneurship level and digital infrastructure level have significantly reduced the generation of land carbon emissions and effectively promoted GUL. Furthermore, the level of green and low-carbon land utilization is often constrained by the application of green and low-carbon land technologies and cannot do without the support of specialized land talents and cutting-edge digital technologies. Therefore, in terms of entrepreneurial activity, the increase in entrepreneurial activity has promoted the cultivation of specialized land talents. The cultivation of specialized land talents can facilitate the introduction of green technologies, ensure the green development of land, enhance the level of green and low-carbon land utilization, curb land ecological environment pollution, and thereby drive the green and low-carbon development of land. From the perspective of the popularity of the Internet, the improvement of digital infrastructure has further promoted the research and development of digital low-carbon technologies, enabling farmers to better achieve lower carbon emissions in land use. While promoting the green development of land, it can also ensure the efficiency of land input and output (Lu et al., 2020; Yu S. et al., 2023). This can not only promote the composite development of agricultural land and the improvement of the level of green land utilization, but also increase investment in smart land through the DE and expand the coverage of low-carbon detection facilities for digital land, thereby achieving a transformation from land transfer to green and low-carbon land utilization. This marks that entrepreneurship and the development of the Internet have entered a new stage of green land development.

Based on this, this paper proposes: Hypothesis 2 (H2): The DE can significantly promote the level of green and low-carbon land utilization through entrepreneurial activity and Internet coverage.

3.3 Heterogeneity effect

Due to the significant differences in the level of digital infrastructure, industrial structure characteristics, and policy implementation capabilities among different regions in China, as well as the varying degrees of emphasis placed by local governments on digital technology empowering GUL, the level of DE in promoting GUL will also show significant variations in different regions. On the one hand, in economically developed regions, the level of digitalization is relatively high. Local governments pay more attention to the coordination between digital governance and the territorial space planning system, achieving in-depth synergy between land development and land carbon reduction. A well-developed digital infrastructure provides a technical foundation for the management of smart farmland and the construction of low-carbon industrial parks, significantly enhancing the efficiency of intensive land use (Almalki et al., 2023; Jan et al., 2023). On the other hand, relatively economically backward regions will generate a "learning effect." However, due to the weak digital infrastructure restricting technological penetration, the development of clean energy and the protection of ecological land mainly rely on exogenous policies such as fiscal subsidies for driving, and the endogenous impetus for low-carbon land utilization is relatively insufficient. This further leads to a deficiency in the promoting effect in economically backward regions or the inability to demonstrate a significant promoting effect in the short term (Liu et al., 2023; Jin and Zhong, 2024).

Based on the above regional differentiation characteristics, this paper proposes: Hypothesis 3 (H3): The DE has a significant heterogeneous effect on GUL.

4 Data and methods

4.1 Model settings

4.1.1 Benchmark model

Based on the above analysis, the following fixed-effect model is constructed to verify the impact of the DE on the low-carbon use of land. Due to the inherent characteristics of each province that do not change over time (such as geographical conditions, historical agricultural structure, and policy traditions), these factors simultaneously affect the process of the DE and the low-carbon use of land. Fixed-effect models can eliminate individual fixed effects (such as provincial dummy variables) through within-transformation, avoiding estimation biases caused by omitted variables. The formula is as follows:

$$GUL_{i,t} = \alpha + \beta_1 DE_{i,t} + \beta_2 X_{i,t} + \mu_i + \varepsilon_{i,t} \quad (1)$$

In Model (1), GUL is the explained variable, representing the low-carbon utilization of land, and DE is the core explained variable, representing the digital economy; X is the set of control variables, and respectively represent the i province, the t period, μ_i represent the fixed effect, and $\varepsilon_{i,t}$ represent the random disturbance term.

4.1.2 Mechanism model

Furthermore, to further examine the possible mediating effect of the digital economy in promoting the green and low-carbon utilization of land, we further incorporate entrepreneurial activity and the level of Internet coverage into the benchmark model (1), extending to model (2):

$$Z_{i,t} = \alpha + \beta_1 DE_{i,t} + \beta_2 X_{i,t} + \mu_i + \varepsilon_{i,t} \quad (2)$$

TABLE 1 Index system for low-carbon land utilization.

Criterion layer	Layer of elements	Indicator layer	Weights
Economic push	Social development	Proportion of urban population to total population at the end of the year/%	0.03
		Per capita disposable income of urban residents/(ten thousand yuan/person)	0.09
	Economic growth	GDP growth rate (over previous year)/%	0.02
	Industrial transformation	Ratio of tertiary to secondary industries/%	0.13
	Scale expansion	New urban construction land area/km^2 in this year compared with the previous year	0.01
Energy consumption	Resource consumption	Residential water consumption per unit of construction land/(ten thousand t/km^2)	0.01
		Quantity of urban construction land consumed per unit of GDP/(km^2/100 million yuan)	0.01
	Energy consumption	Electricity consumption per unit of GDP/(kW·h/100 million yuan)	0.02
	Environmental pollution	Total urban carbon emissions per unit of construction land/(ten thousand t/km^2)	0.03
Low-carbon governance	Green and low-carbon capital investment	Science and technology expenditure per unit of construction land/(ten thousand yuan/km^2)	0.19
	Green and low-carbon labor investment	Annual amount of R&D per unit of construction land/(person-year/km^2)	0.15
	Green and low-carbon governance efforts	Investment in environmental pollution control per unit of construction land/(ten thousand yuan/km^2)	0.18
	Ecological, green and low-carbon guarantee	Urban *per capita* park green area/(m^2/person)	0.13
	Green and low-carbon space development	Green coverage rate of built-up area/%	0.01

TABLE 2 Control variables.

Variables	Code	Definition
urbanization rate	URB	The proportion of the urban population to the permanent resident population in each province
government intervention	FE	The proportion of provincial government fiscal expenditure in the GDP of each province
foreign direct investment	FDI	The proportion of foreign direct investment actually utilized by each province of its GDP
industrial structure	IS	The proportion of the added value of the primary industry in each province to its GDP

In Model (2), $Z_{i,t}$ is the mediating variables of this paper, namely entrepreneurial activity and Internet coverage level, $X_{i,t}$ represent a series of control variables.

4.2 Explanatory variables

4.2.1 Digital economy (DE)

This paper refers to the existing literature (Xu et al., 2025c), and selects the Digital Inclusive Finance index jointly compiled by the Digital Finance Research Institute of Peking University and Ant Financial for representation. The Digital Inclusive Finance Index is formed based on the massive real transaction data of users. Through the reasonable and scientific selection of 33 sub-indices, A relatively authoritative measurement of the development status of digital inclusive finance can also effectively demonstrate the development level of China's DE. And in order to better evaluate the benefits of the DE, we further carried out logarithmic processing.

4.3 Explained variable

4.3.1 Green and low-carbon utilization of land (GUL)

GUL, as the core carrier for the optimal allocation of territorial space, is a key yardstick for measuring the level of ecological civilization construction. The goal is to integrate the advantages of ecological protection red line control, carbon sink resource development, and intelligent monitoring technologies, and inject a continuous low-carbon driving force into regional high-quality development (Eweade et al., 2024). This paper refers to the existing research (Shi and Liao, 2025) and constructs an indicator system

TABLE 3 Descriptive statistics of variables.

Variables	N	Average	Standard deviation	Minimum	Maximum
DE	403	252.40	109.44	16.22	496.88
GUL	403	0.26	0.09	0.13	0.62
URB	403	0.60	0.13	0.23	0.90
FE	403	0.29	0.21	0.10	1.44
FDI	403	14.50	76.07	0.77	984.97
IS	403	0.10	0.05	0.00	0.26
EA	403	1,173.44	1,031	12.80	4,979.70
ICR	403	0.31	0.41	0.10	3.33

including three levels: "economic promotion, energy consumption, and low-carbon governance." These indicators together constitute a comprehensive indicator system for measuring GUL. Unlike most studies, this research particularly conducts an overall assessment of economy, energy, and governance, which not only helps to improve the agricultural industrial environment, but also provides a development direction for achieving sustainable development of the agricultural industry, promoting green agricultural development, and protecting ecological security. The specific measurement indicators for GUL are shown in Table 1.

4.4 Control variables

Considering that there are many factors affecting China's DE and GUL, this paper refers to existing studies (Xu and Lu, 2025a; Wang Y. et al., 2023). On this basis, this paper selects four control variables: urbanization rate, government intervention, foreign direct investment, and industrial structure. In fact, the selection of control variables can effectively avoid errors brought about by research. The four control variables chosen in this paper have a strong correlation with the core explanatory variables and the explained variables of this paper. From the perspectives of urbanization, government, investment, and industry, it can well prove the connection between the digital economy and the green and low-carbon utilization of land. The evaluation after adding control variables can effectively verify the relationship between DE and GUL. The specific results are shown in Table 2.

4.5 Mechanism variables

1. Entrepreneurial activity (EA), as a key engine for resetting the factors of land production and utilization, not only enhances the synergy efficiency between human capital and green and low-carbon technology capital, but also drives a systematic leap in GUL. Referring to the existing research (Tan et al., 2025), the proportion of individual and private employment in the total number of people in each province was used for measurement.
2. Internet coverage rate (ICR): As the core infrastructure for bridging the digital divide, the Internet coverage rate not only significantly lowers the threshold for technology acquisition but also reconstructs the elastic system of agricultural factor substitution. Referring to the existing research (Guan et al., 2023), the number of Internet accesses in each province was used and logarithmic processing was conducted.

4.6 Data sources and descriptive statistics

This paper is based on the current conditions of China's DE and GUL. To reflect the availability and operability of relevant indicators, the original data of relevant variables are from "China Statistical Yearbook," "China Rural Statistical Yearbook," "China Environmental Statistical Yearbook," "China Land Statistical Yearbook," and the Institute of DE of Peking University. Given that the data of various indicators may be missing in different years, in order to obtain as complete a data resources as possible and reflect the latest trends of the DE and GUL, the time range of the sample data in this paper is set from 2011 to 2023. As for the selection of sample regions, due to the limited data from Hong Kong, Macao, and Taiwan regions of China. Therefore, the remaining 31 provinces (autonomous regions) were selected as the objects for analysis and evaluation. The missing parts are filled in by using the linear interpolation method and the exponential smoothing method. The symbols of each variable and the statistical analysis results of their representativeness are shown in Table 3 as follows.

5 Model results

5.1 Empirical strategies and results

This paper first selects the above Formula 1 to evaluate the relationship between DE and GUL, conducts regression analysis using the fixed effects model, and performs regression analysis by adding control variables and by adding control variables. Firstly, the regression results without introducing control variables are examined. The results are shown in column (1) of Table 4. The study finds that without adding control variables, the regression coefficient of the DE is significantly positive at the 1% significance level. It is proven that the DE has a significant promoting effect on GUL. To further improve the accuracy and reliability of the research, in this paper, different control variables are added successively from

TABLE 4 Direct effect.

Variables	(1)	(2)	(3)	(4)	(5)
DE	0.04*** (15.34)	0.03*** (6.07)	0.03*** (5.85)	0.03*** (5.98)	0.03*** (5.71)
URBAN		0.17** (2.17)	0.19** (2.43)	0.14 (1.55)	0.08 (0.89)
FE			0.09 (1.46)	0.08 (1.41)	0.08 (1.43)
FDI				0.01 (1.63)	0.01*** (1.76)
IS					−0.62* (−2.87)
Fixed effects	Control	Control	Control	Control	Control
Cons	0.02 (1.04)	−0.03 (−1.09)	−0.06* (−1.79)	−0.04 (−1.13)	0.06 (1.19)
R^2	0.39	0.40	0.40	0.40	0.42
N	403	403	403	403	403

Note: T-statistics in parentheses; *, **, and *** indicate significance at the level of 10%, 5% and 1%, respectively, and the following tables are the same.

TABLE 5 Endogeneity test and robustness test.

Variables	(1)	(2)	(3)
DE	0.02*** (3.07)	0.03*** (4.74)	0.02*** (4.92)
Control variables	Control	Control	Control
Fixed effects	Control	Control	Control
Cons	0.01 (0.09)	0.13** (2.41)	0.02 (0.68)
N	372	372	403

(2) to (5) for re-regression, in order to capture more accurately the indirect influence of these potential influencing factors on the regression results. The results show that the coefficient of the DE remains positive and is still significant at the 1% significance level. This not only verifies that the improvement of China's DE development level has an important promoting effect on GUL. It is worth noting that the coefficient size of the DE does not change significantly with the introduction of control variables. This can further indicate that the research results of this paper have high robustness and further prove Hypothesis H1.

5.2 Endogeneity test and robustness test

The previous text has demonstrated that the DE has a significant promoting effect on GUL. To better prove the robustness of the baseline regression results, this paper will adopt the following four methods for verification. Furthermore, to avoid the endogeneity problems that may occur in regression, this paper will first conduct endogeneity tests. The specific methods are as follows:

First, the instrumental variable method. Considering that the traditional fixed effect assessment model may have estimation bias and endogeneity problems, this paper selects the lagging period of the DE as the instrumental variable of this paper (Zhu et al., 2022). The specific test results are shown in column (1) of Table 5. Among them, the value of the LM statistic is 351.792 and is significant at the 1% level, which indicates that there is no obvious weak instrumental variable problem in the benchmark regression of this paper. Furthermore, the coefficient value of the Wald F statistic is 6,371.549, which is far greater than the critical value of the 10% significance level. This rejects the null hypothesis that the selected instrumental variable is unidentifiable, proving that the selection of the instrumental variable is scientific and reasonable. At the same time, it also demonstrates that the benchmark regression in this paper will not be affected by endogeneity. Second, the control variable lags behind by one stage. Referring to the existing research methods (Xu et al., 2025d), choosing the one-period lag method of the control variable in the robustness test can not only reduce the endogeneity problem in the estimation of the benchmark model, but also scientifically measure the robustness of the benchmark model. The test results are shown in column (2) of Table 5. The coefficient of the DE is still significantly positive at the 1% level, which can prove the robustness of the benchmark regression results in this paper. Third, change the model. A self-sampling of 1,000 times was adopted as the alternative model (Tan et al., 2025), and the regression results are shown in column (3) of Table 5. The research finds that the impact coefficient of the DE on GUL remains significantly positive at 1%, which once again indicates that the results of the benchmark regression in this paper are robust.

5.3 Heterogeneity analysis

To further clarify the impact of the DE on GUL, the heterogeneous effects of regression in different regions were explored. This not only enriches the understanding of the application effects of the DE, but also provides a more refined perspective for the future formulation of agricultural environmental policies and agricultural development policies.

Due to the differences in resource endowments and economic development stages among different regions in China, the mechanism of the DE's effect on GUL may present significant geographical heterogeneity (Liu and Xia, 2022; Sasse and Trutnevyte, 2023). For this purpose, in this study, the samples were divided into three major regions: the East, the Middle, and the West for group regression. The results in columns (1)–(3) of Table 6 show that compared with other regions, the promoting effect and effect in the eastern region are more obvious. The DE in the

TABLE 6 Distribution heterogeneity.

Variables	(1) Eastern region	(2) Central region	(3) Western region
DE	0.07*** (6.84)	0.01 (1.27)	0.02** (2.53)
Control variables	Control	Control	Control
Fixed effects	Control	Control	Control
Cons	0.56*** (3.29)	−0.06 (−0.82)	0.13** (2.44)
N	143	104	156

TABLE 7 Indirect effect.

Variables	(1) EA	(2) ICR
DE	0.09*** (4.40)	0.04*** (2.71)
Control variables	Control	Control
Fixed effects	Control	Control
Cons	1.07*** (6.04)	−0.43*** (−3.30)
N	403	403

eastern region shows a significant promoting effect on GUL, and its influence coefficient is significantly positive at the 1% level. The reason lies in that the developed eastern regions have accelerated the transformation and upgrading of traditional land use to green and low-carbon use through the DE. They have optimized land use methods by leveraging digital technologies and, at the same time, better developed low-carbon land by taking advantage of the geographical proximity between cities and suburbs, effectively enhancing land use efficiency and land quality. In addition, as the clean energy and digital infrastructure in the eastern region are more complete than those in other regions, they are more capable of providing technical support for green agricultural production methods, thereby further enhancing the capacity for green and low-carbon land utilization. Although the DE in the central region has shown a promoting effect on GUL, it has not passed the significance test, reflecting that the digital finance in this region is still in the stage of scale expansion. Although the utilization efficiency of some resources has been enhanced through industrial integration, the development mechanism for low-carbon land use is still not well established. The depth of research and application of green and low-carbon land technologies is insufficient, which has led to the failure to fully unleash the promoting effect of the DE in GUL. Furthermore, the functional positioning of the central region as a major grain-producing area makes it face more constraints in the process of balancing food security and GUL. The DE in the western region also shows a significant promoting effect on the GUL, with the influence coefficient being significantly positive at the 5% level. This is mainly attributed to the region's innovative promotion of the deep integration of digital technology and land governance, with the smart agriculture platform precisely guiding the fallow rotation of cultivated land and ecological restoration. In addition, the development of e-commerce for characteristic agricultural products has given rise to the shared cold chain logistics model, as well as the widespread application of intelligent irrigation systems in hilly and mountainous areas. Especially in the western region, which is a karst landform area, the construction of an integrated monitoring network for low-carbon land utilization has enabled the DE to effectively resolve the predicament of fragmented land operation and form a new path for enhancing the low-carbon productivity of land through digital empowerment.

5.4 Mediating effect

5.4.1 Entrepreneurial activity level

This study will explore the mediating role of entrepreneurial activities using Formula 2 and conduct regression using the two-step mediating method. The results in column (3) of Table 7 show that entrepreneurial activity has a significant mediating effect on the impact of the DE on GUL. The DE provides a systematic solution for the low-carbon use of land by stimulating the key transmission hub of entrepreneurial activity. The enhancement of entrepreneurial activities promotes the dual empowerment of technological penetration and institutional innovation, further reshaping the transformation of the allocation model of low-carbon land factors.

Firstly, the DE has restructured the dynamic coupling relationship among land, technology, and capital through entrepreneurial activity, promoting the transformation of the traditional high-carbon land use model to a smart and green low-carbon paradigm. In addition, entrepreneurial activities have given rise to innovative business forms for low-carbon land utilization. Through digital platforms, fragmented land resources are integrated to build a governance system that collaborates with new green technologies. In this digitalization process, land elements are concentrating on high-efficiency and green low-carbon industries. Traditional labor is undergoing a deep transformation from extensive farming to digital carbon management services. By deeply integrating data empowerment with ecological constraints, land resources are promoting a coordinated development towards carbon reduction and efficiency improvement.

Secondly, the entrepreneurial activity has established a collaborative governance system for low-carbon land utilization by amplifying the scale effect of digital emission reduction technologies. The wave of digital entrepreneurship has given rise to a rapid growth in the demand for low-carbon technologies, promoting technological innovation in land management and the coordinated upgrading of the human skill structure. Supported by the digital governance platform, the entrepreneurial entities have achieved real-time monitoring and precise regulation of land carbon emission data throughout the process through the linkage mechanism of digital technology and land system adaptation, thereby further enhancing GUL.

Finally, the entrepreneurial activity has catalyzed the adaptive transformation of low-carbon land governance, establishing a regulatory system and policy framework that combines data-driven and market incentives. The entrepreneurial ecosystem driven by the DE promotes the formation of a collaborative land green and low-carbon governance framework with local governments as the leaders, agricultural enterprises as the implementation objects, and consumers as the actual supervisors. In addition, local governments should also rely on entrepreneurial platforms to build an intelligent carbon performance supervision system. New agricultural business entities should introduce cutting-edge grain technologies through digital certification to further promote the green, low-carbon and sustainable development of land.

5.4.2 Internet penetration rate

This study will once again use Formula 2 to explore the mediating role of Internet coverage and also conduct regression using the two-step mediating method. The results in column (2) of Table 7 show that the popularity of the Internet has a significant mediating effect on the impact of the DE on GUL. With the further popularization of the Internet, the structure of information acquisition and digital capabilities has been reshaped. It not only directly breaks down the information barriers for the low-carbon transformation of land, but also relies on the synergy effect of digital technology research and development and technology penetration to comprehensively enhance the internal driving force for the green utilization of land.

Firstly, by improving the digital infrastructure to reconstruct the digital organizational form of land elements, the problems of information silos and regulatory failures existing in traditional land use can be solved, and the high-carbon land use model can be transformed and upgraded towards a green and low-carbon direction. Meanwhile, by optimizing the resource allocation structure through the flow of data elements, the digital infrastructure has been continuously upgraded. This not only effectively promotes the construction of the intelligent land detection platform, facilitating the transformation of land use from the traditional extensive land expansion model to a precise carbon reduction model, but also promotes the construction of high-standard farmland in China, significantly reducing the mechanical energy consumption and chemical dependence per unit of land.

Secondly, with the increase in Internet coverage, the network synergy of digital carbon reduction technologies has been strengthened, significantly enhancing the economies of scale in GUL. In addition, the DE has given rise to the demand for intelligent land governance, further precisely regulating and systematically applying green emission reduction technologies, and promoting the improvement of the skill structure of land use entities towards enhancing land ecological data analysis and land ecological protection decision-making. Meanwhile, the popularization of the Internet can reduce the cost of deeply integrating low-carbon technologies into land production, which is conducive to achieving the simultaneous reduction of resource consumption and carbon emissions.

6 Conclusions and policy recommendations

6.1 Conclusion

In this paper, we have constructed a measurement system for the DE and GUL, explained the promoting role of the DE and GUL from a theoretical perspective, and explored the mechanism of their action. In addition, the panel data of 31 provinces in China from 2011 to 2023 were selected as the empirical evidence for this paper. Three models, namely the panel fixed model, the quantile model, and the mediating model, were respectively used to examine the influence effect, influence mechanism, and heterogeneity between the DE and GUL from multiple perspectives. The main findings are as follows:

First, the results of the benchmark regression indicate that the direct impact of the DE and GUL shows a significant promoting effect. Moreover, after adding various control variables, no significant change was found in this result. Furthermore, after testing endogeneity, we believe that the benchmark regression is scientific and reasonable. We conducted robustness tests through two methods: replacing the model and adding a lag term to the control variables. We found that the core conclusion that the DE promotes GUL has not changed significantly. This conclusion emphasizes that the state should enhance the application of the digital economy in land to promote the green and low-carbon utilization level of land, and is consistent with existing literature. This indicates that the state should vigorously develop the digital economy to improve the green and low-carbon utilization level of land, which can not only better promote economic development but also maintain ecological security.

Secondly, the results of the mediating effect indicate that entrepreneurial activity and Internet penetration rate have significant mediating roles in the assessment of the impact of the DE on GUL. Among them, the increase in entrepreneurial activity and the penetration rate of the Internet is conducive to the exertion of the roles of land production factors and green technology factors, which can reduce the generation of land pollution and provide important support for improving the level of green and low-carbon land utilization. This conclusion provides a specific direction for the Chinese government's future financial input and practical experience for developing countries. It is highly consistent with the existing published literature. This indicates that the country can make good use of the advantages of entrepreneurial activity and the Internet penetration rate to provide a good boost for the development of the digital economy and further reduce the generation of carbon emissions in land use. This ensures the security of the national ecological environment.

Thirdly, the heterogeneity regression results show that in the eastern and western regions of China, the DE has a significant promoting effect on GUL, but it shows no significant effect in the central region. This result indicates that in regions with developed economies and more advanced digital technologies, the advantages of the DE in promoting GUL are more prominent. It further demonstrates that promoting the application of the DE and digital green technologies can more effectively achieve the core goal of low-carbon transformation of land and agriculture. The emergence of this conclusion reflects the imbalance in development among different regions in China, which is consistent with the conclusion of many scholars' research. It can be said that if China wants to achieve green and low-carbon land utilization, it needs to take advantage of the digital economy based on the development status of different regions.

6.2 Policy recommendations

First, develop the capacity for digital land governance and improve the low-carbon land management and control system. The depth of application of digital technology in the land sector is a key support for unleashing GUL and promoting the transformation of land use patterns. We should promote the digital collaboration of coordinating the allocation of land resource elements and carbon emission management, optimize the intelligent collaboration of territorial space planning and ecological carbon sink functions, and accelerate the construction of a digital low-carbon governance system featuring digital agricultural bases, smart energy facilities, and carbon data monitoring networks. Government departments should enhance the digital empowerment level of land low-carbon utilization, leverage the policy guidance role of the digital economy, improve the digital implementation details and intelligent supervision mechanism of land low-carbon utilization regulations, and form a full-process digital monitoring and regulation system for land low-carbon utilization.

Second, build regional differentiated empowerment paths to break through the constraints of the digital divide. In the eastern region, efforts should be made to strengthen the dual-wheel drive of technological adaptation and institutional innovation. Relying on the advantages of digital infrastructure, promote intelligent decision-making systems, pilot "digital land banks" to integrate fragmented and idle land, and release the carbon reduction potential of existing land. Explore the mechanism linking carbon emission rights trading with land development indicators simultaneously. In the western regions, priority should be given to the layout of inclusive digital infrastructure. In the central region, efforts should be focused on breaking through the bottleneck of "technology-system" synergy. In response to the functional constraints of major grain-producing areas, develop a balance model between food security and low-carbon land use; Establish a digital agriculture entrepreneurship incubation park to guide technology to sink to counties at a medium level of development. It is suggested that the government increase investment in the digital technology empowerment and intelligent monitoring platform construction for the low-carbon utilization of land, accelerate the establishment and implementation of data standards and intelligent regulatory systems related to the low-carbon utilization of land, which can not only significantly improve the efficiency of land use and the accuracy of carbon emission control, but also effectively reduce the hidden carbon footprint in the process of agricultural production and construction. Achieve a win-win situation of low-carbon land utilization efficiency and ecological health.

Third, activate the dual intermediary engines of entrepreneurship and the Internet, and enhance the depth of technological penetration. The entrepreneurial activity has been enhanced. A land green technology venture capital fund has been established, and tax credits are provided to agricultural enterprises that adopt technologies such as blockchain traceability and intelligent irrigation. Build a "Digital Agricultural Service crowd sourcing Platform" to guide the labor force to shift from traditional farming to carbon management services. Focus on enhancing the coverage rate of gigabit optical networks and 5G base stations in rural areas of the central and western regions. Establish digital technology promotion stations and, through targeted training, lower the threshold for farmers to apply the smart agriculture platform, thereby solving the problem of implementing green agricultural technologies. It is suggested that the government strengthen the systematic training of digital technology application capabilities for agricultural producers and operators. Through policy guidance and technical support, it should popularize knowledge on data monitoring, intelligent analysis and precise management of low-carbon land use, cultivate compound talents in low-carbon land management who master digital tools, and fully release the comprehensive efficiency of low-carbon land use driven by digital technology.

6.3 Research deficiencies and prospects

Future research can be deepened and expanded from the following two dimensions: First, refine the observation scale and data dimensions. This study uses provincial panel data to reveal the macro impact of the DE on GUL, but the micro transmission mechanism still needs to be analyzed in depth. Subsequently, operational data at the prefectural, county and enterprise levels can be collected. By combining the scale of land transfer, the skills of the labor force and the differences in the integration models of various business entities, the micro-level role path of the DE in GUL can be revealed. Second, strengthen the research on the dynamic coupling of digital economy policies and land policies. The measurement of the digital economy and the green and low-carbon utilization of land in this paper may not be comprehensive. Future research can further construct a dynamic system model that combines climate conditions, technological progress, labor force and land quality, especially the nonlinear matching relationship between the diffusion of green and low-carbon technologies and land use. A more in-depth refinement of the measurement system for the digital economy and the green and low-carbon utilization of land can further reveal the long-term mechanism and spatio-temporal heterogeneity characteristics of the digital economy in the green and low-carbon utilization of land, providing more precise theoretical support for improving the land governance system and achieving ecological and environmental security.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

TL: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft , Writing – review and editing.

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