THE IMPACT OF DIGITAL TECHNOLOGY ON THE EFFICIENCY OF REALIZING THE VALUE OF FOREST ECOLOGICAL PRODUCTS IN CHINA

JIANG, X. M.[1] – GUAN, Z. J.[2*] – ZHANG, W.[2]

[1]*Teaching Department, Changzhou Vocational Institute of Engineering, Changzhou 213164, China*

[2]*Wu Jinglian School of Economics, Changzhou University, Changzhou 213159, China*

**Corresponding author*
e-mail: zhijie.guan@163.com

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Abstract. Forest resources provide extensive ecological services with significant economic and environmental value. In recent years, digital technologies have been increasingly applied to the forestry sector, profoundly shaping the process of realizing the value of forest ecological products. Based on an analysis of the influence mechanism of digital technology on the efficiency of forest ecological product value realization, this study empirically examines the impact of digital technology on the efficiency of forest ecological product value realization by constructing indices for forest ecological product value realization efficiency and digital technology development levels and adopting balanced panel data of 31 provinces from 2014 to 2021. The results show that: (1) digital technology has a significant positive effect on the efficiency of forest ecological product value realization; (2) digital technology significantly promotes the efficiency of forest ecological product value realization through technological innovation and industrial upgrading; (3) there is heterogeneity in the impact of digital technology on the efficiency of forest ecological product value realization, and the level of digital technology in the southern forest area has a positive and significant impact on the efficiency of forest ecological product value realization, however, it shows no significant effect in the northeastern and southwestern forest areas.
Keywords: *digital transformation, ecological value, value realization, panel data analysis, forestry economy*

Introduction

For a long time, the rapid economic development mode has caused serious damage to the ecological environment, an increased demand has occurred for a better environment. The report of the 20th Party Congress proposes accelerating the establishment of an ecological product value realization mechanism, which is becoming increasingly important. Forest ecosystems provide a variety of ecological services and material products for human beings (Xu, 2024), and the value realization of forest ecological products is key to satisfying the demand for high-quality forest ecological products (Liu and Yu, 2022). However, the value realization of forest ecological products faces practical challenges, such as limited trading scope, high transaction costs, and docking difficulties on both supply and demand sides. The CPC Central Committee and the State Council issued the Overall Layout Plan for the Construction of Digital China, which requires "building a green and intelligent digital ecological civilization and accelerating the collaborative transformation of digitization and greening." This points out the direction of practical challenges of realizing the value of ecological products in China, and the exploration and practice of various pilot areas in recent years have also proved that digital technology can empower all aspects of the realization of the value of ecological products. The exploration and practice of the pilot

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areas in recent years has also proved that digital technology can empower the realization of the value of ecological products, and open up the blockage and difficulty of the transformation of the "two mountains."

The term "eco-products" was first proposed in 2010 by the State Council in the National Main Functional Areas Plan, which defines eco-products as all products provided by the natural ecosystem. Realizing the value of ecological products means rationally and effectively realizing the value of ecological products embedded in green water and mountains (Zhu et al., 2023). As one of the important ecological products, various scholars have conducted a series of studies on the realization of the value of forest ecological products. First, some scholars have studied the concepts of forest ecological services and ecological products. Forest ecological products do not have a single, unified definition internationally. The Food and Agriculture Organization (FAO) considers forest ecological products as those produced through forest and resource management, which directly generate economic benefits and also enhance human well-being through ecological services (FAO, 2014). The International Union for Conservation of Nature (IUCN) places particular emphasis on the non-market services provided by forests, such as biodiversity support and water resource protection (IPBES, 2019). Different regions focus on different aspects of forest ecological products, but they generally refer to the various beneficial products and services provided by forest ecosystems through natural processes or human intervention. These beneficial products include tangible material products such as timber and non-timber forest products (e.g., medicinal herbs, fruits, etc.), and these beneficial services include intangible ecological services such as carbon sequestration, biodiversity support, water resource protection, and cultural value (Dou et al., 2022). For example, European and North American countries emphasize the role of forests as carbon sinks and their contribution to climate change mitigation, while developing countries focus on the role of forests in livelihood support, food supply, and sustainable development (Wang and Tian, 2023). The characteristics of forest ecological products in China can be summarized as "a combination of diversity and regionality, emphasis on ecological services and public welfare functions, and a parallel approach of policy-driven support and market-oriented exploration" (Lou et al., 2024). Second, some Chinese scholars have studied the path to realizing the value of forest ecological products. For example, some scholars have summarized the ecological protection compensation model of Ezhou City and the "forest ecological bank" financing model of Nanping City (Liu et al., 2022). Some scholars have analyzed the influence of policy, market, technology, and society on the realization of ecological product value (Li et al., 2023). Some scholars pointed out that the realization modes include ecological industrialized management, green finance, ecological indicator trading, and forest economy (Li and Xie, 2024), and the path of market, government, and government + market as the main body should be established (Zhu et al., 2024). Research on forest ecological product value realization at the theoretical level lays the foundation for measuring the efficiency of forest ecological product value realization (Kong et al., 2022). Wang et al. (2023) constructed an input-output index system of forest ecological product value realization efficiency and measured the realization efficiency of forest ecological product value in Zhejiang Province. Zhang and Qiu (2023) used the Super-SBM model to measure the supply efficiency of forest ecological products in 29 provinces and cities of China from 2011 to 2018. Finally, in recent years, with the development of the digital economy, some scholars have conducted research on the impact of digital technology on the realization of ecological product value. For example, scholars believe that the logic of data-enabled

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ecological product value realization is feasible (Kong et al., 2023), and the digital economy promotes the conversion efficiency of forestry ecological product value (Chen and Zhao, 2022). The value of digitally enabled eco-products should be realized by taking measures in the four links of production, distribution, exchange, and consumption.

The above studies have defined the concept and connotation of forest ecological products, theoretically analyzed the multiple mechanisms of forest ecological product realization, constructed a system of indicators for forest ecological product input, output, and realization efficiency, and formed a relatively perfect measurement method that provides a theoretical basis for the efficiency of digital technology in realizing the value of forest ecological products. However, in the context of the construction of digital China, digital technology is integrated into all aspects of life. Whether the ever-developing digital technology can empower the realization efficiency of forest ecological product value, and how to promote the realization of forest ecological product value has not yet been involved in empirical research. Therefore, this study empirically analyzes the impact of digital technology on the efficiency of forest ecological product value realization by constructing forest ecological product value realization efficiency indices and digital technology development level indices, and puts forward policy recommendations with the expectation of providing policy references to improve the efficiency of forest ecological product value realization.

Theoretical analysis

According to the definition of ecological products in China's "National Main Functional Area Planning", ecological products include fresh air, clean water, and a suitable climate, which are natural elements that maintain ecological balance, regulate the function of the ecological environment, and provide a good living environment for human beings (State Council Office of the People's Republic of China, 2010; Song et al., 2023). An increasing number of scholars believe that ecological products are not only natural elements but also include ecological material, regulating service, and cultural service products, which are the services and material resources provided by natural ecosystems for human survival, production, and life (Li et al., 2023). In this study, combined with existing research, forest ecological products are defined as a general term for various products and services obtained by human beings from forest ecosystems through the co-production of labor and natural elements with natural forest resources as the carrier. The value of forest ecological products includes both economic and ecological values. The value realization models of forest ecological products include forest ecological compensation, forest carbon trading, and forest ecological industries. "Efficiency" refers to the production efficiency in economics, i.e., realizing the maximum output with the minimum input. The efficiency of forest ecological product value realization is to effectively provide more forest ecological products for the market through the input of human, ecological, and material capital elements, to realize the optimal allocation of forest resources, and to realize the transformation of the ecological value of forest ecological products to economic value (Hu and Li, 2023). During the process of economic development, the input of forest ecological product value has a significant impact on economic growth in regions rich in forest ecological resources. The Cobb-Douglas function is the most commonly used model for studying input-output efficiency. Land, physical capital, and labor are traditional input factors, while the value of forest ecological products, as an important concept in modern ecological economic growth theory, will also be included in the system of economic growth factors.

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The production function model transforms into *Equation 1*:

$$Y_{i,t} = A_{i,t}{}^{\mu} N_{i,t}{}^{\alpha} K_{i,t}{}^{\beta} R_{i,t}{}^{\gamma} E_{i,t}{}^{\delta} \lambda_{i,t} \tag{Eq.1}$$

Taking the logarithm of *Equation 1* yields *Equation 2*:

$$lnY_{i,t} = \mu lnA_{i,t} + \alpha lnK_{i,t} + \beta \ln K_{i,t} + \gamma \ln R_{i,t} + \delta \ln E_{i,t} + \ln \lambda_{i,t} \tag{Eq.2}$$

In *Equations 1* and *2*: Y_{it}, N_{it}, K_{it}, R_{it}, E_{it} and A_{it} denote the value-added of forestry industry, input of forest land, input of physical capital, input of labor force, value of forest ecological products and other inputs of the ith provincial unit in year t, respectively. α, β, γ, δ and μ denote the output elasticity of input of forest land, input of physical capital, input of labor force, value of forest ecological products and other inputs, respectively. λ denotes the constant term. The digital technology improves the transformation efficiency of forestry ecological products by influencing forestry production factors and industrial transformation. The digital technology brings scale advantages to forestry, promotes the industrialization of forest ecological products, and reduces transaction costs and promotes the optimal allocation of resources through the Internet platform. In addition, a sound digital infrastructure can also help promote the digitalization of forestry and improve the transformation efficiency of the value of forest ecological products.

Digital technology is supported by big data and information technology, with massive data as the key production factor, and data as a new type of production factor has become a new kinetic energy source for the development of forest ecological products, promoting the realization of the value of forest ecological products (Wang et al., 2024). Digital technology in the forest field and forest resources investigation, creation, cultivation, protection, and forestry first, second, and third industry development and other aspects of link integration, can accurately empower the development of forest eco-products (Chen et al., 2023), to realize the forest resources from the collection, processing, to the sale of links in the whole process of digital management and monitoring, to ensure that the ecological products are traceable and quality and safe, and to accelerate the expansion of the market for forest eco-products and competitiveness enhancement and provide better experience for consumers. The development of the forest industry platform economy overcomes the geographical barriers to forest product trade, reduces the transaction cost of forest products, expands the trading scope of forest ecological products, and promotes the development of new forms and new business forms. Therefore, this study hypothesis 1: digital technology has a positive effect on the efficiency of forest ecological product value realization.

In the era of the digital economy, data elements such as new kinetic energy increase economic benefits and ecological efficiency through technological innovation, providing new kinetic energy for forest ecological product value realization. Digital technological innovation makes the whole life cycle of forest organisms always in a state of intelligent decision-making, promotes intelligent manufacturing and production mode upgrading of forestry enterprises, and effectively improves the innovative output and production efficiency of forest products (Koji et al., 2007). At the same time, relying on digital technology empowered the monitoring of forest ecology, and the whole life cycle of forest resources, digital supervision for climate regulation, water conservation, soil stabilization, sand prevention, and other forest ecological product services play an important role. In addition, digital technology innovation contributes to the digital

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transformation of the traditional forestry industry and the integration of the digital industry, forming new forest digital products and production methods, consumption patterns, and modes of forest ecology (Zhu et al., 2018). With the innovation of digital technology, digital forest ecological products have gradually diversified, and are able to meet people's increasingly diversified consumption needs. Digital technological innovation has enabled the establishment and improvement of digital platforms, accelerated the circulation and sale of forest ecological products, and promoted the transformation and upgrading of forest ecological product consumption. Therefore, this study proposes hypothesis 2: Digital technology has a positive role in promoting the efficiency of forest ecological product value realization through technological innovation.

Digital technology has given rise to forestry-related emerging industries, and "forestry Internet+" promotes the upgrading of industrial structures. The upgrading of the industrial structure of the forestry industry changes the forestry industry from the traditional production and processing of trees to the diversified mode of forest management and forest tourism, extends the value chain of the forestry industry, and enhances the ecological service value of forest ecological products (Han and Chen, 2022). The upgrading of the industrial structure has shifted the forestry industry to secondary and tertiary industries, and the proportion of the primary industry has decreased. The output values of the three industries have a strong correlation with air pollution; the higher the output value of the primary and secondary industries, the more air pollutants are discharged, and the output value of the tertiary industry is the opposite of air pollutant emissions (Xu et al., 2024). The adjustment of the industrial structure helps to significantly enhance the ecological function of China's forests by increasing the amount of carbon sequestration, oxygen release, and absorption of pollutant gases (Zhang and Xiong, 2020). Therefore, this study hypothesis 3: digital technology has a positive effect on the efficiency of forest ecological product value realization through industrial upgrading.

According to the distribution characteristics of forest resources, China's forest regions are divided into northeastern, southwestern, and southern forest regions. The northeastern forest area includes Heilongjiang, Jilin, Liaoning, and Inner Mongolia; the southwestern forest area includes Yunnan, Sichuan, and Tibet; and the southern forest area includes Zhejiang, Anhui, Fujian, Jiangxi, Guangdong, Guangxi, Hubei, Hunan, Guizhou, and Hainan. The northeast forest area is China's largest state-owned forest area, the southwest forest area is China's important tropical forest area, and the southern forest area is China's third largest natural forest area. The three major forest ecological products of forests have obvious differences. At the same time, there is spatial heterogeneity in the level of digital economic development, showing an obvious step from the east coast to the inland (Xu et al., 2024), and the digital infrastructure, digital application level, and informatization level of forest areas are not balanced. Due to the cold climate and relatively inconvenient transportation, the digital infrastructure in the northeastern forest region is weak, the application of digital technology is still in its infancy, the application of intelligence and information technology is relatively small, and the technological investment is relatively limited. Digital technology applications in the southwestern forest region are mainly focused on ecological protection, forest disaster monitoring, and biodiversity conservation. In recent years, with the development of big data and Internet of Things (IoT) technologies, breakthroughs have been made in ecological environment monitoring and precise forest management, but the overall application is still in its early stages (Jiang and Jiang, 2021). The southern forest region has a relatively mature level of information

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construction and service coverage. The digital technology applications in this region are quite advanced, especially in forestry production and management, such as remote sensing monitoring of forest resources, big data analysis in forestry, and intelligent forest management (Gao, 2016). Gaps in digital technology in China’s three main forest regions can have different impacts on the realization of forest ecological product values. Therefore, this study hypothesis 4: there are regionalized differences in the impact of digital technology on the efficiency of forest ecological product value realization.

The influence of digital technology on the efficiency of forest ecological product value realization is shown in *Figure 1*.

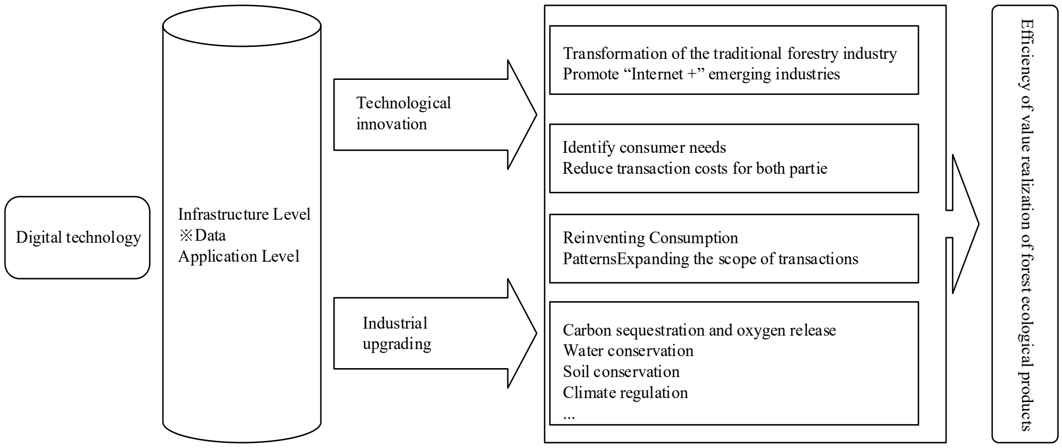

Figure 1. *Mechanisms of digital technology’s influence on the efficiency of forest ecological product value realization*

Materials and methods

Indicators of forest ecological product value efficiency and digital technology development

Indicator system for forest ecological product value realization efficiency

This study draws on the research of Zhang and Xiong (2020) and considers the accessibility of data to establish the forest ecological product value realization efficiency indicator system. Input indicators include capital factor input, labor factor input, and land factor input, which are expressed by the number of people employed in forestry at the end of the year, forestry capital factor input expressed by the cumulative investment in forestry since the beginning of the year, and land factor input expressed by the area of forestry land. Output indicators. The value of forest ecological products includes both economic and ecological values. In terms of economic value, the total output value of forestry production is selected, that is, the sum of the output value of the first, second and third industries of forestry. in terms of ecological value, the ecological value of forest ecological products is reflected by the natural resources of forests as the material carrier of the ecological value. The ecological benefits of forest ecosystem services are also reflected in forest resources, and academics usually consider the ecological parameters related to the total amount of forest resources as important indicators for measuring the value of ecosystem services (Zhao et al., 2020). Therefore, in this study, forest accumulation and cover were selected as ecological value indicators (*Table 1*).

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***Table 1.** Forest ecological product value efficiency indicator system*

Type of indicator	Level 1 indicators	Secondary indicators	Indicator measurement modalities
Input indicators	Capital factor inputs	Forestry investment completion	Cumulative investment completed since the beginning of the year/$
	Labor factor input -/%	Number of people working in the forestry system at the end of the year	-/Person
	Land factor inputs	Forestry land area	-/10,000 ha
Output indicators	Economic benefit	Gross value of forest production	-/Billion dollars
	Ecological benefit	Forest stock	-/Billion cubic meters
		Forest cover	-/%

Indicator system of digital technology development level

This paper refers to the evaluation standard of the National Statistical Information Center on the level of digital technology development and draws on the research of Zhao et al. (2020) to construct an indicator system for the level of digital technology development with three indicators: the level of digital infrastructure, the level of digital technology application, and the level of digital technological innovation (Tone and Tsutsui, 2009), which is shown in *Table 2*.

***Table 2.** Digital technology development level indicator system*

Standardized layer	Specific indicators	Unit	Indicator properties
Level of digital technology infrastructure	Fiber optic line length	Kilometer	+
	Internet broadband access interface	Ten thousand	+
	Mobile telephone exchange capacity	Ten thousand households	+
Level of application of digital technology	Internet users per 100 population	Household	+
	Cell phone penetration rate	%	+
Level of innovation in digital technology	Proportion of local financial expenditure on science and technology in the fiscal budget	%	+

The coverage of fiber-optic networks, popularization of the Internet, and scenario-based applications in forest areas present a characteristic of “gradient advancement across the Eastern, Central, and Western regions, with breakthroughs in key areas”. The construction of fiber-optic networks in forest areas focuses on “core management and protection zones as well as key protected areas”, prioritizing the resolution of core needs such as fire prevention and forest management. Remote areas still rely on satellite and wireless communication for supplementation.

The Chinese government has promoted the extension of network services to deep mountain forest areas through policies like the “Telecommunications Universal Service Pilot Program” and the “Radio and Television Border Solidification Project”. Key forest areas have initially formed a three-dimensional coverage network integrating “fiber optics + 4G/5G + satellite”. For instance, Inner Mongolia Forest Industry Group, through

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government-enterprise cooperation, has built 5269 km of transmission optical cables and 221 4G base stations, establishing an integrated coverage system combining public networks and forestry private networks. This has addressed the long-standing poor communication issue in the northern forest areas.

The Internet penetration rate in forest areas is significantly influenced by population density and economic development levels. High coverage has been achieved among forest management personnel and in core areas, while the penetration rate in residential areas and remote regions remains lower than the national average.

Model setting

To analyze the promotion effect of the digital technology level on the efficiency of forest ecological product value realization, this study constructs the following panel data model, which can be expressed as *Equation 3*:

$$VREF_{it} = \alpha_1 + \alpha_2 DIG_{it} + X_{it}\eta + u_i + \varepsilon_{it} \quad \text{(Eq.3)}$$

where i denotes region, t denotes time, $VREF_{it}$ denotes the efficiency of forest ecological product value realization in region i in period t, DIG_{it} is the level of digital technology development as an explanatory variable, X_{it} denotes a series of control variables affecting the efficiency of forest ecological product value realization (the level of economic development, the openness of the region, and the degree of financial intervention in the forestry industry), u_i denotes the unobservable effect affecting the efficiency of forest ecological product value realization, and ε_{it} denotes the random error term. Product value realization efficiency, u_i denotes the unobservable effect, and ε_{it} denotes the random error term.

The GLS method (Generalized Least Squares) is a linear regression model adjustment algorithm designed to handle heteroscedastic data or sequences with serial correlation. Its core principle involves modifying the estimation strategy of traditional least squares through the use of a weighting matrix. To select the appropriate estimation method for the panel data, this study follows a standard testing procedure. First, the F-test is used to determine whether a fixed-effects model is superior to a pooled Ordinary Least Squares (OLS) model. Second, the Lagrange Multiplier (LM) test is conducted to decide between a random-effects model and pooled OLS. Finally, the Hausman test is employed to choose between the fixed-effects and random-effects models. This systematic approach ensures that the most suitable model is selected for robust empirical analysis.

Selection of variables and data sources

Variable selection

(1) Explained variables. Forest ecological product realization efficiency (VREF) was measured using the Super-SBM model. The Super SBM model is based on the SBM model. The SBM model is capable of measuring the efficiency of evaluation units from non-radial and non-angular perspectives. It introduces slack variables into the objective function, which can reflect input redundancies or output shortfalls in the production process. However, the SBM model yields a maximum efficiency value of 1, making it impossible to further compare research subjects that also have an efficiency value of 1. The Super-SBM model solves the defect of the SBM model that the efficiency value is limited to 1, makes up for the deficiency of the SBM model in efficiency measurement,

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and is widely used in efficiency measurement (Qiu, 2022). In this paper, we select a non-radial Super-SBM model that considers slack variables from both input and output perspectives under the condition of variable returns to scale. The specific form of the Super-SBM model is expressed by *Equation 4*:

$$\mathrm{Min}\theta^* = \frac{1}{m}\sum_{i=1}^{m}\frac{X_i}{X_{ik}} \quad \text{(Eq.4)}$$
$$\text{s.t: } \sum_{j=1, j\neq k}^{n} x_j\lambda_j ; \sum_{j=1, j\neq k}^{n} y_j\lambda_j \leq \bar{y} ;$$
$$\sum_{j=1, j\neq k}^{n} x_j\lambda_j + s_i^- = X_{ik},\ i = 1,2,3,..m$$
$$\sum_{j=1, j\neq k}^{n} y_r\lambda_j - s_i^+ = y_{rk},\ i = 1,2,3,..s$$
$$\sum_{j=1, j\neq k}^{n} \lambda_j = 1, \bar{x} \geq x_k, \bar{y} \geq y_k, j = 1,2,3..n\ (j\neq k)$$
$$\bar{y} \geq 0, \lambda \geq 0, s_i^- \vec{r_0}, s_i^+ \geq 0$$

In the above equation, θ* represents the efficiency value of forest ecological product value realization; x and y denote the input and output variables for forest ecological product value realization, respectively; (x, y) represents the reference point of the decision-making variables; m and s refer to the number of input and output indicators, respectively; s^- and s^+ are the slack variables for inputs and outputs, respectively; and λ is the weight vector. When $\theta^* \geq 1$, it indicates that the evaluated decision-making unit is efficient, meaning that the forest ecological product value realization efficiency of that province is effective. Conversely, when $0 \leq \theta^* \leq 1$, it signifies that the evaluated decision-making unit is inefficient, indicating a loss in the forest ecological product value realization efficiency. In such cases, the input-output ratio should be appropriately adjusted.

(2) Core variables. The digital technology development level (DIG), digital infrastructure level (DIG_1), digital technology application level (DIG_2), and digital technology innovation level (DIG_3) were measured using the entropy power method with the help of stata16 software. The entropy value method calculates the entropy value of each indicator according to the impact of the change of the value of each indicator on the whole, and then determines the weights. The larger the entropy value of the indicator, the smaller the weight, relative to the entropy value method, the hierarchical analysis method is too subjective, the entropy value method eliminates the influence of subjective factors, enhances the comparative analysis between the evaluation indicators, and has become a commonly used evaluation method (Wu et al., 2022). This paper also applied the entropy value method to measure the level of digital technology development in each province (Wu et al., 2022; Dong et al., 2017). The measurement steps are as follows:

Step 1: Standardization of data, positive indicators are treated as in *Equation 5*.

$$X_{ij}' = \frac{X_{ij}\text{-Min}X_{ij}}{\text{Max}_{ij}\text{-Min}x_{ij}} \quad \text{(Eq.5)}$$

Step 2: The share of Xij in indicator pij is calculated as in *Equation 6*.

$$p_{ij} = \frac{X'_{ij}}{\sum_{i=1}^{n} X_{ij}'} \quad \text{(Eq.6)}$$

Step 3: Calculate the information entropy ej of the jth indicator according to *Equation 7*.

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$$e_j = -\frac{1}{\ln k}\sum_{i=1}^{n} p_{ij}\ln p_{ij} \quad \text{(Eq.7)}$$

Step 4: The variance index dj for the jth indicator according to *Equation 8*.

$$d_j = 1\text{-}ej \ (j = 1,2,...,n \quad \text{(Eq.8)}$$

Step 5: Calculate the weights of the evaluation indicators as in *Equation 9*.

$$w_j = \frac{d_j}{\sum_{j=1}^{m} d_j} \quad \text{(Eq.9)}$$

Step 6: Calculate the level of development as in *Equation 10*.

$$S_i = \sum_{j=1}^{m} w_j X_{ij}' \quad \text{(Eq.10)}$$

In the above equation, i represents province in China, j represents year. X_{ij} assumes that the original data matrix X consists of m samples and n indicators, X = (X_{ij})m*n, and Xij represents the secondary indicators. The score of each level 1 indicator in the text is the sum of the product of the weights of the level 2 indicators multiplied by the value of the standard indicators, and the level of development of digital technology in each province is derived from the sum of the scores of the relevant level 1 indicators.

(3) Control variables. In this study, we add economic development level (EDQ), regional openness (OPEN), forestry fiscal intervention (GI), value of Forest Ecosystem Services (VFEC) as control variables. These variables also exert influence on the efficiency of ecological product value realization.

Economic development level. A higher level of economic development often implies better Infrastructure, greater market demand, and more financial support for forestry, which may positively influence the efficiency of value realization. The higher the level of economic development, the higher the overall development level of the region may be, and the higher the efficiency of forest ecological products realization. In this paper, we refer to the study of Bei et al. (2023). and express it as the logarithm of the per capita gross regional product of each province (Kong et al., 2023).

Regional openness. A higher degree of openness can facilitate the inflow of advanced technologies, management practices, and capital, and expand market access for forest ecological products, thereby potentially enhancing efficiency. The degree of regional openness affects the degree of attraction of digital talent and digital technology, and the greater the degree of regional openness, the greater the degree of attraction to them, which in turn promotes the level of regional economic development. In this study, we refer to the methodology of Kong et al. (2023) and express it in terms of the logarithm of total trade exports and imports.

Forestry fiscal intervention (GI), fiscal expenditure is one of the important means for the government to maintain economic stability. Government financial support for agriculture, forestry, and water affairs can directly impact investment in forestry infrastructure, ecological compensation, and technological adoption, thus affecting value realization efficiency. Referring to the study of Ren and He (2022), and considering the availability of data, we use the logarithm of the local fiscal expenditures on agriculture, forestry and water affairs in each province to express it (Fang and Fu, 2024).

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Value of Forest Ecosystem Services (VFEC). The total ecological value of China's forests, grasslands, and wetlands amounts to 28.58 trillion yuan (NFGA, 2021). This value represents the comprehensive assessment of ecological regulation services (such as carbon sequestration and climate regulation) and ecological products (such as timber and medicinal materials) provided by these ecosystems. Among these, the total output value of the forestry and grassland industries reached 10.496 trillion yuan in 2024 (NFGA, 2025), yet significant potential remains for realizing the value of ecological products. The magnitude of forest ecosystem services' value reflects the potential for value transformation (Shen et al., 2023). The higher the value of forest ecological products, the greater the efficiency with which they are converted into economic value. Following the methodology of Xie et al. (2015), we employed the equivalent factor method to calculate the ecological service values of forest ecosystems across the following domains: climate regulation, biodiversity conservation, gas regulation, food production, raw materials, recreation and culture, waste treatment, water conservation, and soil formation and protection.

(4) Mediating variables. Industrial upgrading (IUP), adopting Fang and Fu's (2024) approach, is expressed as the proportion of forestry secondary and tertiary industry output value to the total forestry output value (Huang et al., 2023).

Technological innovation (GEFF), drawing on Huang et al.'s (2023) approach, uses the number of patents authorized in the province/local financial expenditure on science and technology to measure the innovation capacity of the province.

Data sources

The data related to forestry in each region regarding the efficiency of forest ecological product realization were obtained from the China Forestry Statistical Yearbook and the China Forestry and Grassland Statistical Yearbook. Data related to the level of digital technology development, level of economic development, regional openness, and degree of financial intervention in forestry were obtained from the statistical yearbook of each province and the China Statistical Yearbook. Some of the missing variable data were filled in using moving average interpolation. Considering the possible heteroskedasticity of the data, the level of economic development, regional openness, and forestry financial intervention were logarithmically processed, and the balanced panel data of 31 provinces (autonomous regions and municipalities directly under the central government) were obtained for the period–2014-2021. The descriptive statistics of the relevant variables are shown in *Table 3*.

Table 3. *Descriptive statistics*

Variable	Obs	Mean	Std. Dev.	Min	Max
VREF	341	0.6953	0.5486	0.0268	2.4567
DIG	341	0.2649	0.1548	0.0227	0.8204
EDQ	341	55437.5	28705.6	15908.2	187508
OPEN	341	13700	22400	31	130000
GI	341	550.3733	277.6667	91.7800	1339.3600
IUP	341	0.5057	0.2435	0.0061	0.9089
GEFF	341	0.5811	0.1332	0.2508	1.0822
VFEC	341	4730	4210	35.43493	20600

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Results

Analysis of the benchmark regression results

Table 4 reports the empirical results on the efficiency of forest ecological product realization and level of digital technology development. Columns (1) to (4) estimate model (1) using mixed effects estimated by the least squares (OLS) method, random effects estimated by the GLS method, fixed effects estimated by the least squares (OLS) method, and fixed effects with the addition of robust standard errors, respectively; at the same time, the four regressions are subjected to the LM test, the F-value test, and Hausman test; the LM test shows that the P-value is 0.0000, which indicates that the random effect model is better than the mixed OLS model; the F test first shows that the F-value is 68.83, and the P-value is 0.0000 less than 0.05, which rejects the original hypothesis, that is, the fixed effect is better than the mixed effect; the Hausman test shows that the P-value is 0.0000, which rejects the original hypothesis, that is, the fixed effect model is used instead of the random effect model. This study also includes robust standard errors in the fixed effects for regression (Column (4) of *Table 4*) to mitigate the effect of heteroskedasticity. The regression results show that the level of digital technology development has a positive and significant effect on the efficiency of forest ecological product realization, and Hypothesis 1 is valid. China's rapid economic development and expanding openness, coupled with increased forest ecosystem service value driven by intensified ecological conservation and restoration efforts, have effectively enhanced the efficiency of realizing forest ecosystem product value. However, the relative decline in forestry fiscal intervention has diminished this efficiency (Kong et al., 2022).

Table 4. *Benchmark regression results*

Variables	(1) VREF (OLS)	(2) VREF (RE)	(3) VREF (FE)	(4) VREF (FE_Robust)
DIG	1.015*** (4.50)	0.808*** (3.23)	0.825*** (3.12)	0.825** (1.79)
EDQ	0.219*** (4.47)	0.185** (1.17)	0.108 (0.61)	0.109 (0.34)
OPEN	0.719*** (5.13)	-0.030 (-0.89)	-0.053 (-1.27)	-0.054 (-1.24)
GI	-0.517*** (-34.32)	-0.206*** (-2.53)	-0.187** (-2.07)	-0.187** (-1.33)
VFEC	0.019*** (2.13)	0.099** (1.39)	0.117** (0.39)	0.117* (0.32)
Constant	-0.170 (-0.37)	1.033 (0.56)	2.282 (0.49)	2.282 (0.48)
Observations Number of id R-squared	341 31 0.303	341 31 0.267	341 31 0.225	341 31 0.225
LM inspect	1173.64***			
F inspect			68.83***	
Hausman inspect		8.29*		

*** denotes $p < 0.01$, ** denotes $p < 0.05$, * denotes $p < 0.1$; t-values are in parentheses

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Test of mediation

The test of the mediation effect in this study adopts the bias-corrected nonparametric percentile bootstrap method, that is, based on the original data (sample size of 341) sampled 1000 times, to obtain the use of bias-corrected 95% confidence interval for the mediation effect, and if none of the intervals include 0, it means that there is a mediation effect; and vice versa, there is no mediation effect. The results are presented in *Table 5*. (1) Mediating effect of technological innovation. In the relationship between the level of development of digital technology and the efficiency of forest ecological product realization, the mediating role of technological innovation is significant, with an indirect effect value of 0.1555 and a 95% confidence interval of (0.056088-0.1156053), and the mediating effect accounted for 20.22% of the total effect; (2) the mediating role of industrial upgrading. In the relationship between the influence of the level of digital technology development on the efficiency of forest ecological product realization, the mediating role of industrial upgrading is significant; the value of the indirect effect is 0.2048, the 95% confidence interval is (0.1371341-0.5467638), and the mediating effect accounts for 27.34% of the total effect. Hypotheses 2 and 3 are thus established.

Table 5. *Intermediation effects*

Brokering model	Direct effect	Indirect effect [95% conf. interval]	Efficacy as a percentage of
Mediating role of technological innovation: digital technology → technological innovation → efficiency of forest ecological product realization	0.6977 [0.2190646-1.17643]	0.1515 [0.056088-0.1156053]	0.2022
Mediating role of industrial upgrading: digital technology → industrial upgrading → efficiency of forest ecological product realization	0.7401 [0.2854497-1.194759]	0.2048 [0.1371341-0.5467638]	0.2734

Heterogeneity test

Tables 6 and *7* represent the results of testing the influence of digital technology and its three dimensions on the efficiency of forest ecological product value realization in the three major forest areas, respectively. The results show that the level of digital technology development and its two dimensions (the level of digital technology infrastructure and the level of digital technology innovation) in the Northeast Forestry Region do not have a significant impact on the efficiency of forest ecological product value realization; the impact of the level of digital technology application in the Northeast Forestry Region on the efficiency of forest ecological product value realization is significantly negative at the 5% level. The effect of digital technology and its three dimensions on the efficiency of forest ecological product value realization in the Southwest Forest Region are not significant. The level of digital technology and digital technology infrastructure in the southern forest region significantly contributes to the efficiency of forest ecological product value realization at the 1% level. There is a difference in the effect of the level of digital technology development on the efficiency of forest ecological product value realization in the three forest regions, and hypothesis 4 is valid.

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Table 6. *Impact of digital technology on the efficiency of forest ecological product value realization in the three forest regions*

Variables	Northeastern forest region	Southwest forest region	Southern forest region
DIG	-0.744 (-0.45)	-0.030 (-0.05)	2.330*** (3.27)
Constant	11.938 (0.54)	27.116** (1.51)	-45.595*** (-3.03)
Observations	44	33	110
Number of id	4	3	10
R-squared	0.56	0.84	0.38
id FE	YES	YES	YES
Year FE	YES	YES	YES

*** denotes p < 0.01, ** denotes p < 0.05, * denotes p < 0.1; t-values are in parentheses

Table 7. *Impact of the three dimensions of digital technology on the efficiency of value realization of forest ecological products in three forest regions*

Variables	Northeastern forest region			Southwest forest region			Southern forest region		
	(1) VREF	(2) VREF	(3) VREF	(1) VREF	(2) VREF	(3) VREF	(1) VREF	(2) VREF	(3) VREF
DIG1	0.506 (0.53)			0.127 (0.24)			3.086*** (4.09)		
DIG2		-8.310* (-1.50)			-1.998 (-0.89)			5.814 (0.62)	
DIG3			-2.584 (-1.64)			-1.188 (-0.54)			2.814 (1.18)
Constant	17.201 (0.71)	2.845 (0.18)	15.881 (0.65)	24.952* (1.47)	20.016 (1.07)	35.007* (1.61)	-46.543*** (-3.44)	-26.373 (-1.55)	-38.236 (-2.78)
Observations	44	44	44	33	33	33	110	110	110
Number of id	4	4	4	3	3	3	10	10	10
R-squared	0.45	0.55	0.45	0.83	0.79	0.80	0.37	0.40	0.43
id FE	YES	YES	YES	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES	YES	YES	YES

*** denotes p < 0.01, ** denotes p < 0.05, * denotes p < 0.1; t-values are in parentheses

Robustness and endogeneity tests

To verify the reliability of the benchmark regression estimation results further, robustness tests were conducted on the sample range and estimation method. Column (1) in *Table 8* shows the results of the robustness test after adjusting for the sample range. The results show that the impact of the level of digital technology development on the efficiency of forest ecological product realization is still significantly positive. Column (2) shows that the impact of digital technology on the efficiency of forest ecological product value realization is still significantly positive using principal component analysis to obtain the level of digital technology (DIG') and regression (Li and Ruan, 2023), confirming the robustness of the results of the previous study. Column (3) shows the

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results of the regression using the Tobit model, and the direction of the effect of the level of development of digital technology on the efficiency of forest ecological product realization is significantly positive, consistent with the results of the benchmark model. Therefore, the conclusion that the level of digital technology development contributes significantly to the efficiency of forest ecological product realization is robust.

To mitigate the potential endogeneity problem, this study adds two-period lagged variables of forest eco-product realization efficiency to the model and tests them using a dynamic panel system GMM model (Column (4) of *Table 8*). The results show that AR (1) and AR (2) reject and accept the original hypotheses, respectively, and pass the original hypothesis that there is no second-order serial correlation in the perturbation term. The Hansen test rejects the original hypothesis of the existence of over-identification constraints, indicating that the instrumental variables are valid. The direction of the effect of the level of digital technology development on the efficiency of forest ecological product realization is significantly positive, which is consistent with the results of the benchmark model, further indicating that the benchmark regression model is robust. In addition, we use an instrumental variable approach to testing. Drawing on the research by Li et al. (2023), we use the interaction term between the number of Internet users (YHS) and the number of cell phone subscribers (YDS) in each region as an instrumental variable for the regression. The instrumental variable is selected to regress the interaction term between the number of Internet broadband access subscribers and the number of cell phone subscribers in each province and city. The results of columns (5) in *Table 8* show that the F value is 120.10, which is greater than 1, indicating that there is no problem with weak instrumental variables and that the instrumental variables selected in this study are reasonable and valid. The P-value of LM is significant, and the original hypothesis of “insufficient identification of instrumental variables” is rejected. This shows that, after considering the endogeneity problem, the effect of digital technology on the efficiency of forest ecological product realization is still significant.

Table 8. *Robustness and endogeneity tests*

	(1) VREF (excluding municipalities)	**(2) VREF (substitution of explanatory variables)**	**(3) VREF (Tobit)**	**(4) VREF (system differential)**	**(5) HQD (instrumental variable approach)**	
					Phase I	**Phase II**
DIG’		0.101** (2.37)				
L2.VRREF				0.030 (0.13)		
DIG	1.112*** (4.35)		0.857** (2.39)	1.067* (1.65)		0.935** (2.18)
YHS × YDS					6.54e-08** (9.87)	
Observations	297	341	341	248	341	341
LM value					7.58**	
F value					72.67	
Adj R^2					0.050	
Wald Chi2					40.47	
Hansen test p-value				0.876		
AR (1) test p-value				0.002		
AR (2) test p-value				0.008		

*** denotes $p < 0.01$, ** denotes $p < 0.05$, * denotes $p < 0.1$; t-values are in parentheses

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Discussion

The empowering role of digital technology

Digital technology has a positive contribution to the efficiency of forest ecological product value realization. This is consistent with the studies of Kong et al. (2023) and Xu et al. (2024) on the development of digital technology to promote high-quality development in the field of ecological products. Kong et al. (2023) took the counties of Lishui City, Zhejiang Province as a sample and found that through the development of digital technology, the value transformation efficiency of forest ecological products was improved, and there was a significant positive correlation between the level of digital economy development and the value transformation efficiency of forest ecological products in each county unit. In the era of digital economy, the three basic links of "production-circulation-consumption" of forest ecological products have been digitized through the empowerment of digital technology, which provides a new impetus for the realization of the value of forest ecological products, and also creates new opportunities for solving the difficulties in docking the supply and demand of forest ecological products, the high cost of transactions, the lack of quality traceability mechanism, product homogenization and many other realistic dilemmas (Felardo et al., 2024).

Mediating mechanisms: technological innovation and industrial upgrading

Regarding mediation effect, technological innovation presents the role of mediating effect. First, technological innovation can improve product quality and traceability mechanism. Through the application of digital technology, the whole life cycle monitoring and management of forest ecological products can be realized to ensure product quality and safety. Second, technological innovation can reduce transaction costs and market information friction. The application of digital technology can optimize the forest ecological products market transaction information, reduce information asymmetry, and thus reduce transaction costs. In addition, technological innovation can enhance the competitiveness of forest ecological products market. Through brand building and market promotion, technological innovation can stimulate a stronger "long-tail effect" and improve consumer recognition of the value of forest ecological products. Finally, through the progress of scientific and technological means, the protection and management of forest resources in the process of realizing the value of forest ecological products can be carried out more scientifically and efficiently. Industrial upgrading shows the role of mediation effect. Industrial upgrading can improve the efficiency of forest ecological product value realization, through improving production factors, changing industrial structure, improving production efficiency and product quality, as well as optimizing the industrial chain, so as to promote the value realization of forest ecological products. For forest ecological products, on the one hand, optimizing the industrial structure through industrial development and linkage, optimizing the allocation of various types of resource elements, etc., tapping and revealing the intrinsic value of the natural ecology, promoting the preservation and appreciation of the value of the forest resource assets, which in turn further promotes the transformation and upgrading of the industry, and gives rise to more new forest ecological industrial forms. On the other hand, industrial upgrading implies the improvement of production efficiency and product quality, and the implementation of a strict quality control system to ensure the quality and safety of forest ecological products. In summary, technological innovation and industrial upgrading play significant mediating roles in realizing the value of forest ecological products.

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Technological innovation provides solid technical support for the efficient realization of forest ecological product value by enhancing product quality, reducing transaction costs, increasing market competitiveness, and optimizing resource management. While, industrial upgrading further promotes the efficiency of forest ecological product value realization by optimizing industrial structure, improving production efficiency and product quality, and perfecting the industrial chain. The two complement each other and work together to promote the realization of the value of forest ecological products.

Regional heterogeneity and its implications

Regarding heterogeneity, when exploring the impact of digital technology development on the value transformation efficiency of forestry ecological products, we should fully consider the heterogeneity between different forest areas. This heterogeneity is mainly reflected in the uneven level of digital technology development in each forest area, which leads to significant differences in the degree of influence of digital technology on the efficiency of value transformation of forestry ecological products. The influence of the level of digital technology development and digital technology innovation on the efficiency of forest ecological product value realization in the Northeast Forest Region is not significant, and the development of digital economy is relatively backward. The effect of the level of digital technology application on the efficiency of forest ecological product value realization in the Northeast Forest Region is significantly negative at the 5% level. The reason for this may be that the economic development rate of the Northeast region has plummeted, and the population outflow and aging phenomenon are serious. In recent years, the economic growth rate of the Northeast region has slowed down, and the traditional industries are facing the pressure of transformation, which leads to the overall lack of economic vitality, which in turn affects the input and application of digital technology. In addition, the Northeast region faces serious a serious brain drain situation. The brain drain limits the pool of digital technology talent and the ability to innovate. The effect of digital technology and its three dimensions on the efficiency of forest ecological product value realization in Southwest Forest Region is not significant. The reason for this may be the low level of economic development, insufficient investment, and insufficient digital innovation capacity in the southwest forest area. The overall economic development level of the southwest forest area is low, and the local financial investment is limited, which leads to insufficient funds for the research and development and application of digital technology, making it difficult to form a scale effect. The complex geographic environment and ecological conditions of the southwestern forest area, as well as the diverse types and uneven distribution of forest resources, make the popularization and application of digital technology face greater challenge. The level of digital technology and digital technology infrastructure in the Southern Forestry Region contributed 1% to the efficiency of forest ecological product value realization. One possible reason is that the economy of the southern forest area is relatively developed, which provides sufficient financial support and market demand for the research, development and application of digital technology. Also the southern forest area has rich forest resources and superior ecological environment, and digital technology can better play its role and improve the efficiency of value transformation in this context. In addition, the digital infrastructure in the southern forest area is more complete, with wide network coverage and fast data transmission speed, which ensures the efficient application of digital technology in all aspects of forest ecological products and effectively improves the efficiency of realizing the value of forest ecological products.

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Limitations and future research directions

Despite its contributions, this study has several limitations that open avenues for future research. First, as noted by the reviewers, the indicators used to measure the level of digital technology development are at the provincial level and are not specific to the forestry sector. Future research could benefit from more granular, sector-specific data, such as the adoption rate of precision forestry technologies, the use of e-commerce platforms for forest products, or the coverage of IoT monitoring systems in forest areas. This would provide a more direct and nuanced understanding of digitization's impact.

Second, this study measures the output of forest ecological products using economic and general ecological indicators. It does not fully capture the unutilized potential of various ecosystem services, such as cultural, recreational, and biodiversity values, which are often difficult to quantify. Future studies could employ more comprehensive valuation methods, such as contingent valuation or travel cost models, to incorporate these non-market values and assess how digital platforms (e.g., for ecotourism or carbon offsetting) help realize this untapped potential.

Finally, this research focuses on the provincial level. Given the significant variations within provinces, future studies employing county-level or firm-level data could reveal more detailed insights into the mechanisms at play.

Conclusions

Based on the theoretical framework proposed in this study, an indicator system is constructed. Balanced panel data of 31 provinces from 2014 to 2021 were used to empirically analyze the impact of digital technology on the efficiency of forest ecological product value realization. The conclusions are as follows: (1) Digital technology has a positive effect on the efficiency of forest ecological product value realization. (2) Digital technology has positively promoted the efficiency of forest ecological product value realization through technological innovation and industrial upgrading. (3) There are regionalized differences in the impact of digital technology on the efficiency of forest ecological product value realization. The impact of digital technology on the value realization efficiency of forest ecological products in the southern forest area has a promotional effect at the 1% significance level, and the improvement in the level of digital technology infrastructure also promotes the improvement in the value realization efficiency of forest ecological products, while the impact of digital technology on the value realization efficiency of forest ecological products in the northeastern and southwestern forest areas is not significant.

This paper draws the following policy insights into the research conclusions: (1) Organically combine forest resources and digital technology to create more synergistic and efficient forest ecological digital application scenarios, to continuously improve the efficiency of forest product value realization through the integration of digital technology and forestry, and vigorously promote the digital industrialization and digitization of the forestry industry. (2) Enhance the capacity of technological innovation, and shape the new advantages of green development. Strengthening the supply of core digital technology and accelerating the overall layout of green technology innovation actively play a fundamental role in the realization of the value of digital technology in forest ecological products, and deeply promote the integration of digital technology and forest ecological products. (3) Promote the upgrading of the forestry industry. To deeply integrate the data elements into the forestry industry chain, promote the synergistic

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development of ecological and economic benefits in the value realization of forest ecological products. (4) Pay attention to the regional differences, and take the road of differentiated development to realize the value of forest ecological products. Southern forest areas should improve the application level of digital technology in the realization of the value of forest ecological products based on the existing level of development, so as to provide a reference for the development of other forest areas and play a role in radiation. Northeastern forest areas are rich in resources but lack labor, and new digital technology and equipment should be promoted to improve the mechanization level. Although the southwestern forest area is rich in forest resources, the relationship between the value of forest ecological products and ecology in the southwestern forest area is characterized by industrial profit but ecological damage; therefore, it is necessary to continuously transform and upgrade, taking into account both ecology and economy.

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Data availability. The data involved in the study can be provided upon request from the corresponding author/authors for any reasonable reason.

Consent to publish. This manuscript has not been published or presented elsewhere in part or in entirety, and is not under consideration by another journal. All the authors have approved the manuscript and agree with submission to your esteemed journal.

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