Frontiers in Forests and Global Change

TYPE Original Research
PUBLISHED 26 January 2026
DOI 10.3389/ffgc.2025.1725074

The impact of digital government development on total factor productivity in forestry: evidence from China

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RECEIVED 14 October 2025
REVISED 03 December 2025
ACCEPTED 15 December 2025
PUBLISHED 26 January 2026

CITATION
Chen H, Zhuang C, Liu M, Xie S, Dong B and Chen L (2026) The impact of digital government development on total factor productivity in forestry: evidence from China. *Front. For. Glob. Change* 8:1725074. doi: 10.3389/ffgc.2025.1725074

Introduction: Enhancing the total factor productivity (TFP) of forestry ecosystems is central to shifting the forestry industry toward high-quality development. This study investigates the impact of digital government initiatives on forestry ecosystem TFP to understand how digital governance can drive ecological and economic efficiency.

Methods: Utilizing panel data from 30 Chinese provinces between 2015 and 2022, this study employs a Dual Machine Learning (DML) model to mitigate endogeneity and estimation bias. This rigorous methodological framework allows for a precise quantitative assessment of the effects and transmission mechanisms of digital government development on forestry ecosystem TFP.

Results: The empirical results demonstrate three key findings: (1) The expansion of digital government significantly boosts the TFP of forestry ecosystems. (2) Mechanism analysis identifies three primary channels for this improvement: the cultivation of new quality productive forces, the upgrading of forestry industrial structures, and the simplification of operational processes. Furthermore, the broader digital economy acts as a significant positive moderator in this relationship. (3) Heterogeneity analysis reveals that the magnitude of these effects varies across regions, contingent upon local economic development levels and forest resource endowments.

Discussion: Based on these findings, the paper proposes policy recommendations to foster institutional innovation, accelerate digital government construction, and implement region-specific strategies. Globally, this study provides empirical evidence for the synergy between digital governance and ecological sustainability. It offers a replicable model for other nations seeking to leverage digital tools to balance economic growth with environmental conservation, thereby contributing to the advancement of global ecological civilization and sustainable development goals.

KEYWORDS

advancement of forestry industrial structure, digital government, new quality productivity, rationalization of forestry industrial structure, total factor productivity in forestry ecology

1 Introduction

As the foundation of terrestrial ecosystems and a key industry in the development of ecological civilization, forestry not only carries out essential tasks like manufacturing tangible goods and providing timber resources, but it also has several social obligations, such as regulating the climate, conserving water, storing carbon, and releasing oxygen. As a result, forestry development has emerged as a key concern for the long-term viability of the economy and society. China's overall forestry output value has been increasing steadily in recent years, crossing the 10 trillion yuan threshold in 2024, according to data from the National Forestry and Grassland Administration.[1] Tens of millions of people in both urban and rural areas now have direct jobs thanks to it, and its contributions to the national economy are becoming more and more substantial. This growing importance of forestry is mirrored globally, as forests are increasingly recognized for their critical role in climate change mitigation and biodiversity conservation. International frameworks like the Paris Agreement and the UN 2030 Agenda for Sustainable Development highlight the pivotal role of forests in regulating climate, enhancing biodiversity, and contributing to sustainable economic growth (Savaresi, 2016; Weiland et al., 2021). For instance, the EU Green Deal and the global push for carbon trading and forest-based carbon credits further emphasize the need for integrating sustainable forest management practices into broader environmental and economic policies. China, as part of its commitment to international environmental goals, has embraced these global frameworks, underscoring the importance of a green development strategy that balances ecological and economic outcomes. Nevertheless, despite its quick progress, the forestry industry's modernization still faces many obstacles: Both resource scarcity and structural imbalances have resulted from conventional large-scale manufacturing strategies (Ning et al., 2021); Inadequate competitiveness in the market (Ning et al., 2021); Industrial upgrading is hampered by forest products' low added value (Xu et al., 2024). Above all, the forestry ecological goods' commercial potential, including carbon sequestration and forest wellness services, has not yet been fully fulfilled (Kong et al., 2022; Lin et al., 2024). In practice, relying solely on market self-regulation often fails to enhance green production efficiency. This failure stems from structural challenges such as the strong externalities of ecological benefits, inefficient technology diffusion, and insufficient factor inputs. Therefore, sustainable improvement requires greater reliance on local governments to implement macro-level regulation using contemporary governance techniques (Fu and Mei, 2023). Thus, improving forestry productivity—in particular, striking a balance between ecological and economic benefits—has emerged as a crucial concern for the high-quality development of forestry in light of this. "High-quality development" is not merely a descriptive term but a distinct stage of economic development proposed in China's new era, marking a transition from rapid quantitative growth to a focus on quality and efficiency. Theoretically, it is underpinned by the "New Development Philosophy," which prioritizes five key dimensions: innovation, coordination, greenness, openness, and sharing. In the specific context of forestry, high-quality development entails a structural transformation from a resource-dependent model focused on timber volume to an innovation-driven model that balances ecological security with economic value. It emphasizes the optimization of total factor productivity (TFP) to achieve sustainable growth that meets societal demands for both ecological services (e.g., carbon sequestration, biodiversity) and high-value forest products. Digital technologies like artificial intelligence, cloud computing, and big data are developing quickly these days. A new model of digital government that naturally combines digital technology and governance theory has emerged as a result of the growth of the digital industry throughout the process of government reform and innovation that followed the New Public Management movement (Li, 2024). It offers a fresh approach to implementation and a focus point for raising the overall factor productivity of forestry ecosystems. The foundation of this governance paradigm is the thorough integration of state-of-the-art digital technologies into all facets of government management, including big data, the Internet of Things, artificial intelligence, cloud computing, and blockchain. Coordinated social governance, accurate management services, efficient use of public resources, and scientific government decision-making are the goals of this strategy.

Increasing the total factor productivity of forestry ecosystems is the primary aim and focal point for the forestry sector to shift toward high-quality growth as the forestry economy moves from seeking quantity to increasing quality (Wang, 2020). One of the most important metrics for assessing the development of sustainable forests is the forestry ecological total factor production. It stands for total factor productivity that simultaneously takes environmental contamination and resource restrictions into consideration. Based on land, labor, capital, and energy inputs, this statistic shows the economic and ecological benefits of forestry as well as the successful management of undesirable outputs like contamination of the environment. It accurately depicts the general effectiveness and sustainability of the development of forests (Liu and Li, 2020). From an output standpoint, there are three main ways that the digital government raises the forestry ecosystems' total factor productivity: Large-scale activities are made possible by the digital government's effective integration of fragmented forest land resources through the advancement of digital services like land transfer and the use of digital platform construction to promote economic development (Hou et al., 2025). To steer forestry toward high-value industries like deep processing and biomass energy, investments in digital infrastructure will rise concurrently. This will expand industrial chains and expand chances for economic value addition. The Forest Chief System is empowered by the digital government to advance ecological development through intelligent management based on the "Five Greens" paradigm. It builds intelligent risk early-warning systems and an integrated terrestrial-aerial-space ecological monitoring network by utilizing digital technology. This greatly increases the resilience of forest ecosystems and their ability to endure disasters by enabling real-time, accurate evaluation and dynamic management of ecological environment quality (Dong et al., 2025). The digital government uses sophisticated digital monitoring to keep an eye on corporate production and activities in order to reduce environmental damage. At the same time, it uses data analytics to accurately provide farmers with subsidies and other incentives, promoting environmentally friendly production methods. This strategy reduces the adverse externalities of forestry output and stops environmentally damaging activities at their source (Zhang and Jing, 2024). In conclusion, digital government increases the overall factor productivity of forestry ecosystems by reducing environmental externalities, protecting ecosystem health, and improving economic efficiency in a synergistic manner.

At the nexus of the development of the digital era and the establishment of an ecological civilization, research on digital

1 http://202.99.63.178/search/608871

government and the total factor productivity of forestry ecosystems is a cutting-edge topic. The following two aspects are the main focus of existing investigations. First, when creating indicators for total factor productivity in forestry, researchers are starting to focus on ecological characteristics and sustainable development aspects as the idea of green development becomes more widely accepted. This change represents a departure from the conventional emphasis on the output of total forestry production value as the main focus of research paradigms (Su et al., 2015). Increasing gradually to include elements like environmental degradation and ecological advantages in a thorough analysis (Lü et al., 2022; You et al., 2025), represents the increasing focus on the multifunctionality and green transformation of forestry development in the academic community. Second, there is a growing body of studies on how digital governance affects total factor productivity (Qi, 2024; Su et al., 2024; Lun and Liu, 2024). These studies show that digital government, as a contemporary governance paradigm, optimizes administrative procedures, improves public service effectiveness, and lowers institutional transaction costs, thereby fostering a more transparent and efficient business environment for a range of economic entities. Consequently, this has a favorable effect on the growth of total factor productivity in every area of the national economy. However, despite the growing body of literature, significant gaps remain. First, the majority of existing studies on digital governance have concentrated on conventional economic sectors like manufacturing (Mou et al., 2025; Zeng et al., 2025) and services (Peng and Peng, 2025; Lü et al., 2025), with limited attention paid to the unique characteristics of the forestry sector. Second, while international research has explored digital platforms and technologies in forestry (Holopainen et al., 2015; Roos et al., 2021; Ali et al., 2025), these studies often operate under different institutional, economic, and forest tenure contexts compared to China's state-led, macro-regulation oriented digital government model. Consequently, there is still a dearth of research on how digital governance specifically boosts the total factor productivity (TFP) of forestry ecosystems, despite the sector's strong externalities and complex ecological functions. This gap underscores the novelty of examining the Chinese digital government model specifically for its impact on forestry ecological TFP. To bridge these gaps, this study investigates the relationship between digital government and total factor productivity in forestry ecosystems from multiple dimensions. It creatively incorporates three important mediating variables—new-quality productive forces, forestry industrial structure rationalization, and forestry industrial structure upgrading—while assessing direct effects. By doing so, this strategy seeks to address the "black-box" understanding of the impact pathways of digital government in current research, thereby providing scientific backing for the high-quality growth of China's forestry industry.

2 Theoretical analysis

According to public governance theory, governments can improve the effectiveness and legitimacy of public services by implementing transparent, coordinated, and participative governance systems. Public governance theory emphasizes multi-stakeholder participation, collaboration, and communication more than standard government management models do. It emphasizes how society, the market, and the government work together to promote the sustainable, efficient, and fair use of resources (Katsamunska, 2016). By leveraging information platforms and data-driven decision-making, digital government enhances governance modernization, efficacy, and transparency. This approach, in turn, improves the effectiveness of forest resource use and strengthens ecological conservation. First, by reducing information asymmetry in forestry production processes, digital government improves the scientific rigor of ecological decision-making in forestry. Forest ecosystems encounter issues including fragmented data and delayed information acquisition under traditional governance frameworks, which lead to imprecise decision-making. Digital government creates dynamic, real-time forestry ecological monitoring and early warning systems by utilizing cutting-edge technology including big data, the Internet of Things, remote sensing, and artificial intelligence. These technologies make it possible to precisely track important data, such as changes in forest resources, the spread of illnesses and pests, and the likelihood of fires. For example, high-frequency, high-precision data on the health of forests can be obtained using drone-based remote sensing technologies. When used in conjunction with big data analysis, it offers prompt alerts for regions susceptible to disease and pest outbreaks, directing focused prevention and control initiatives to reduce resource losses (You et al., 2024). Forestry management authorities can shift from "experience-based" to "science-based" approaches thanks to this data-driven decision-making model, which lowers resource waste and blind investments while directly improving the effectiveness of forestry production and ecological conservation. Second, by encouraging interdepartmental cooperation, digital government eliminates the silo effects that come with traditional governance. Because it involves several government agencies, including those involved in natural resources, environmental protection, water conservation, agriculture, and rural affairs, as well as research institutes, social organizations, and other stakeholders, forestry ecological governance is complicated due to its cross-regional and cross-departmental nature. The efficacy of governance as a whole is seriously hampered by the "information silos" and "overlapping responsibilities" that are often produced by traditional decentralized management. By creating a single forestry management information platform and data exchange mechanism, digital government accomplishes data interoperability and operational coordination across several agencies (Dong et al., 2024). For example, we may more thoroughly evaluate the condition and possible threats of forest ecosystems by combining and evaluating data on water resources from water conservancy departments, climate data from meteorological departments, and forest resource data from the forestry industry. This facilitates resource sharing and cooperative operations while allowing for quick coordination of multi-departmental responses to crises like floods and forest fires. The overall productivity of forest ecosystems is indirectly increased by this collaborative governance model, which also lowers governance costs resulting from gaps in interdepartmental coordination and speeds up and improves responses to difficult forestry ecological concerns. Third, by increasing public participation, digital government revitalizes social governance. The government should not be the only entity in charge of forestry ecological governance; widespread public participation is also essential to enhancing the sustainability and efficacy of governance. Digital government offers a variety of channels for public involvement in forestry ecological governance by creating user-friendly and effective online platforms for public engagement, data transparency platforms, and multimedia science communication channels. For example, regular people can participate in online oversight of the "forest chief system" or report unlawful logging and forest fire dangers via smartphone apps. Environmental groups can create a bottom-up system for supervision and policy suggestions by using ecological data that has been made public by the government to support their own independent study and public campaigning. By include forest farmers, social groups, academic institutions, and even the general public in the chain of forest ecological conservation and management, this model expands the range of governance players. A favorable environment marked by "government leadership, social participation, and multi-stakeholder governance" has been established by it (Sun and You, 2024). In addition to offering important information and oversight for forestry ecological governance, active public participation also improves policy acceptance and implementation, lowers resistance to governance, and indirectly supports the growth of total factor productivity in forestry ecology. The following hypothesis is put out in this study based on the analysis above:

> *H1*: The development of digital government helps to raise the forestry ecosystems' overall factor productivity.

A key institutional safeguard and technological platform for igniting and fostering new productive forces is the growth of digital government. In particular, it necessitates a significant investment in the development of digital infrastructure, including large data centers, cloud computing, 5G, and high-speed networks, in order to offer the fundamental support for the collection, transmission, and processing of enormous volumes of forestry ecological data. This makes it possible for data to actually emerge as a crucial element that propels innovation. With the help of 5G networks and the growing use of integrated remote sensing systems that cover land, the sky, and the air, data on forest changes, pest infestations, carbon sequestration levels, and other topics may be transmitted in real time with high precision. This offers a steady flow of new information for astute analysis (Wang et al., 2025). Second, by strengthening changes to simplify administration, assign authority, and enhance government services—all the while encouraging the transparent exchange of public data—the digital government maximizes the delivery of public services. This strategy successfully fosters the creative life of research institutes and market entities (Wei, 2025). For example, the "One-Stop Online Service" lowers institutional transaction costs by expediting the clearance procedure for forestry research projects. In the meantime, operators are encouraged to maximize production by the blockchain-based forest rights registration system, which improves the efficiency and transparency of forest rights transfers. In order to support new businesses and technologies like intelligent breeding and deep processing of forest products, the public data open platform offers a wealth of resources for research and development in interdisciplinary sectors including forestry, biotechnology, artificial intelligence, and novel materials. These are the primary expressions of new, high-quality forces of production. Last but not least, the digital government uses its strong data analytics and predictive powers to more precisely identify the forestry sector's shortcomings and determine its future development paths at the macro level. This makes it possible for supportive policies to be specifically formulated in order to direct creative resources, such as finance, talent, and technology, toward critical emerging forestry sectors with low energy consumption and high added value, like carbon credit trading, eco-tourism, and smart forestry (Scholz et al., 2018). In the forestry industry, fresh, high-quality productive forces can quickly attain economies of scale and clustering effects thanks to this methodical institutional setup and resource distribution. It drives the transformation and upgrading of traditional forestry toward intensification, intelligence, and greening, hence transforming its wide development model. This establishes a strong "new-quality" basis for raising forestry ecosystems' overall factor production.

The total factor productivity of forestry ecosystems is increased by new-type productive forces, which are distinguished by their high technological content, high-efficiency performance, and high-quality development. On the one hand, new-type productive forces greatly increase the efficacy and efficiency of forestry production elements through model transformation and technical innovation. For instance, using high-precision drones and robotics for afforestation, forest care, harvesting, and fire protection can significantly lower labor expenses and operational risks while increasing labor resource productivity (Shah et al., 2024). However, by creating an intelligent system for ecological monitoring, early warning, and restoration, new-quality productive forces improve the sustainability and resilience of forest ecosystems, guaranteeing steady, long-term production increase (Cao et al., 2025). Big data-based forest fire risk prediction models and AI-driven intelligent pest and disease identification and early warning systems allow for early detection and accurate response for ecological threats, averting significant losses. At the same time, the use of genetic technology and novel materials in ecological engineering speeds up the recovery of ecological services by improving the efficacy, efficiency, and cost of restoring degraded ecosystems. The total factor productivity of forest ecosystems is increased as a result of this clever improvement of risk management and forest ecosystem health, which guarantees that these ecosystems can produce more consistent and superior ecological services and products. The following hypothesis is put out in this study based on the analysis above:

> *H2*: By encouraging the emergence of new, high-quality productive forces, digital government development can raise the overall factor productivity of forestry ecosystems.

Its capacity for accurate identification, dynamic matching, and optimal allocation of forestry resource elements reflects the influence of digital government on the rationalization of the forestry industry structure. Due to information asymmetry and data gaps, traditional forestry management frequently faces structural problems such incorrect forest land utilization, poor tree species selection, and unbalanced input–output ratios. Through the use of remote sensing imagery and high-precision geographic information systems, digital government creates a "digital profile" of forestry resources. This makes it possible to conduct thorough surveys and evaluations of the different types of forest land, soil fertility, climate, tree growth status, and even the distribution of pests and diseases. This makes it possible for the government to accurately direct the idea of choosing the appropriate tree for the appropriate location in various forest regions using scientific information rather than human opinion. By ensuring that the tree species planted in each forest plot are the most appropriate for its ecological conditions, it maximizes the structure of forest resource usage and prevents waste from careless afforestation or improper tree species selection (Haji et al., 2020). Second, digital government can achieve structural balance in the forestry industry by creating an interconnected data platform for the entire chain. This will

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help with inventory optimization and supply–demand matching at every stage of forestry production, processing, and distribution. Historically, a lack of knowledge about the forest product market frequently caused a gap between supply and demand, which resulted in things like timber stockpile and unsold non-timber forest products. Economic losses and resource waste resulted from this. The digital government's platform may gather data on market consumption demands, processing facility capacity, and timber harvesting volumes in real time. It gives forestry operators accurate market guidance using sophisticated algorithms for predictive analysis (Holzinger et al., 2022). For instance, by providing early warnings about possible overabundance of specific forest products, the platform can help forest farmers modify their planting schedules or harvesting strategies. Simultaneously, it can reduce losses in intermediary linkages and transportation expenses by dynamically matching harvesting schedules in forest areas with the raw material demands of processing firms. Greater coordination in the pace and size of production across all forestry sector segments is made possible by this data-driven integration of production, supply, and sales. It increases the turnover efficiency and sensible use of forestry resources by preventing resource idleness or overconsumption brought on by structural imbalances. Lastly, by digitizing standardized management and performance evaluation, the digital government encourages the standardization and efficiency improvement of forestry management models, which optimizes internal organizational and management structures in the forestry industry. Conventional forestry operations lack standardized operational standards and performance evaluation methods and involve multiple entities with differing management capabilities. The digital government makes it possible for national forestry policies, technical standards, and operational guidelines to be intelligently interpreted and disseminated through digital platforms, guaranteeing that forestry management departments and operational entities at the grassroots level understand and apply them accurately. For instance, scientific methods like fire patrols, insect and disease control, and thinning can be standardized and illustrated by creating an app for forestry operations assistance. This improves the uniformity and effectiveness of field operations by making it possible for forest farmers and rangers to acquire and use these techniques. At the same time, digital government projects can use data to statistically assess the economic performance of various forestry operators, ecological benefit outputs, and resource usage efficiency. Ineffective management procedures or operational models can be found using data feedback systems, allowing for focused policy recommendations or improvement suggestions. In the forestry industry, the digital approach to performance orientation and precision management has made it easier to optimize management procedures and flatten organizational structures. It has achieved a general simplification of the structure of the forestry industry by making forestry production and management more efficient, standardized, and scientific (Damaševičius and Maskeliūnas, 2025).

By increasing factor allocation efficiency, decreasing systemic losses, and bolstering ecosystem stability, the forestry industry structure can be rationalized. This will have a pull effect on the overall factor productivity of forestry ecosystems. Ecological resilience is naturally higher in a well-managed forest stand structure, which includes a balanced age structure, a healthy stand density, and the right species composition of trees. This makes it more resilient to the effects of climate change and natural disasters like windstorms and wildfires, which lowers the productivity losses brought on by these occurrences. The continuous increase and sustainability of total factor productivity in forest ecosystems are ensured by the efficient management of systemic risks and the removal of internal redundancy, which allow production to continue with fewer losses and more stability (Jiang et al., 2024). However, by removing internal redundancies and reducing systemic hazards, simplifying the structure of the forestry industry lowers inefficiencies in forestry production and raises the overall factor productivity of forestry ecosystems (Chen et al., 2025). Irrational industrial structures frequently result in poor risk resilience, overproduction or underproduction, and resource misallocation. After the structure is rationalized, losses from unsold forest products or shortages of raw materials can be minimized through clever supply and demand balance regulation. Large-scale outbreaks of forest pests and diseases can lead to yield losses and ecological damage; however, these can be avoided with accurate early warning and control strategies. Furthermore, an ecologically resilient forest stand structure is fundamentally defined by a balanced age structure, a healthy stand density, and a suitable tree species mix. Because of their resilience, forests are better equipped to endure the effects of climate change and natural disasters like windstorms and fires, which lowers the production losses brought on by these occurrences. Forest ecosystems are able to maintain production with reduced losses and increased stability thanks to the efficient management of systemic risks and the removal of internal redundancy, which guarantees consistent growth and sustainability in total factor productivity. The following hypothesis is put out in this study based on the analysis above:

> *H3*: By encouraging the simplification of the forestry industry structure, digital government development can raise the overall factor productivity of forestry ecosystems.

The ability of the digital government to create digital platforms that foster an innovation ecosystem and to combine and activate high-end variables is what propels the development of the forestry industry structure. Talent shortages, capital constraints, and technical bottlenecks are some of the obstacles preventing conventional forestry sectors from progressing to higher levels. On the one hand, we offer strong computational capabilities and data resources to enable the R&D and application of cutting-edge forestry technologies by developing a national-level forestry big data and cloud computing platform. For example, AI algorithms can speed up the production of biomass materials, intelligent breeding, and even the use of gene editing technologies to better forest trees by utilizing the platform's extensive genetic information and climate models (Yasin et al., 2025). Conversely, digital government speeds up the digitization of assets and the conversion of data into a crucial component, drawing and directing social capital, elite talent, and other resources toward developing forestry industries. Industrial upgrading is fueled by this (Li and Zhang, 2025). The high risks and lengthy return cycles of traditional forestry investments make it challenging to draw in social capital. To accomplish digital rights confirmation, quantitative evaluation, and trade of ecological assets, such as forest carbon sinks, biodiversity protection services, and ecotourism resources, digital government makes use of technologies like blockchain and the Internet of Things. For example, digital platforms that post forest carbon sink monitoring data and trade regulations make it easy and transparent for both individuals and corporations to participate in carbon trading. By doing this, the ecological value of forests is converted into measurable financial assets, opening up new avenues for forestry funding. It draws social capital, such as venture capital and green financing, to high-value industries like the production of smart forestry equipment, high-tech breeding, and forest ecosystem services. At the same time, we have aligned our online learning platform and database of forestry specialists with the demand for top personnel from forestry research institutions and new businesses. This program has supported the development of human resources in the forestry industry by facilitating the entry of creative and knowledge-based talent.

The enhancement of total factor productivity in forestry ecosystems is largely dependent on the development of the forestry industry structure. While advanced development is fueled by technology innovation, conventional improvements in forestry ecological total factor productivity frequently depend on management improvements or increases in input amounts (Shi et al., 2025). The maturation cycle of forest trees can be greatly shortened and output per unit area increased by selectively cultivating new varieties with high carbon sequestration capacity, rapid growth rates, and strong stress tolerance through molecular breeding of forest trees made possible by genomics and big data technologies. In the processing of forest products, the deep integration of cloud computing and industrial IoT allows for completely automated and intelligent production lines, significantly increasing conversion rates from logs to high-value panels and furniture while lowering waste emissions and energy usage. This causes forestry ecosystems' total factor productivity to develop at a leapfrog rate. However, by increasing forestry service activities and generating new value, the modernization of the forestry sector structure improves the overall factor productivity of forestry ecosystems and results in a qualitative change in total forestry output (Yang et al., 2025). The main output of traditional forestry is physical items like lumber, which have little added value and are quite vulnerable to changes in the market. Progress represents a substantial broadening of the breadth of forestry's output—from "cutting trees to sell wood" to "selling ecological services, green technologies, and cultural expressions." For example, the marketization of ecological value produced by forestry in carbon sequestration is made possible by forest carbon sink services that use blockchain technology to guarantee data transparency. The ecological beauty and health advantages of forestry are transformed into high-value service offerings through immersive forest tourist experiences driven by VR/AR technology and sophisticated ecological wellness principles. Forest ecosystems may provide much more comprehensive value with the same resource inputs because to this structural upgrading, which involves moving from a focus on material products to a balance of material goods and services and from primary products to high-value-added commodities. As a result, it significantly raises forest ecosystems' overall factor productivity. The following hypothesis is put out in this study based on the analysis above:

> *H4*: By encouraging the modernization of the forestry industry structure, digital government development can raise the overall factor productivity of forestry ecosystems.

According to an opportunity-driven viewpoint, the sophisticated digital economy acts as a new kind of external environment and infrastructure, creating more conducive circumstances for digital government projects aimed at raising the overall factor productivity of forestry ecosystems. The degree of growth of the digital economy dictates the technical support capability and extent for executing digital government policies at the level of technological infrastructure. For example, strong communication networks, Internet of Things technologies, and big data platforms allow for more effective and real-time monitoring of forest resources and information exchange in areas with developed digital economies. Digital governments can take advantage of these technological advancements to improve production choices, more accurately regulate forest resources, and raise overall factor productivity in forestry operations. Conversely, it is challenging to properly execute many digital government programs in areas with lower levels of digital economic growth due to a lack of data resources and a weak network infrastructure. As a result, their capacity to raise forestry ecosystems' total factor productivity is greatly reduced (Lin et al., 2024). The influence of digital government policies is increased by the new market opportunities and resource integration platforms that the digital economy provides from the standpoint of market and resource allocation. The extensive use of digital financing, smart supply chains, and e-commerce platforms has decreased transaction costs for forestry products and increased market access in areas with developed digital economies. In highly developed digital economies, digital government programs that facilitate online timber trading or digital logistics may be more successful. Such actions increase forestry productivity and ecological advantages by lowering intermediary stages and promoting direct producer-consumer relationships. On the other hand, forestry producers find it challenging to obtain timely market information or digital financial help in areas with underdeveloped digital economies due to poor market digitization. The impact of digital services offered by governments on increasing total factor productivity in forestry ecosystems is still quite small (You et al., 2025). The function of digital government in increasing total factor productivity in forestry is positively supported by the digital environment created by the digital economy, according to the innovation ecosystem. Strong digital innovation ecosystems are typically formed in highly digitalized areas because they draw more digital talent and technical R&D activity (You et al., 2024). New forestry technology applications and business models (such smart forestry and forest carbon credit trading platforms) are more likely to be sparked by digital government actions in these areas, such as encouraging the spread of forestry technology and permitting open data sharing. The overall factor productivity of forestry ecosystems will rise as a result of this technological development. However, due to a lack of innovation determinants, areas with low levels of digital economic development find it difficult to convert incentives for digital governance into observable innovation outcomes. Due to a lack of technical advancement, the rise of total factor production in forestry ecosystems has slowed (Lun and Liu, 2024). The following hypothesis is put out in this study based on the analysis above:

> *H5*: Through the growth of digital government, the digital economy contributes positively to the regulation of forestry ecosystems, increasing their total factor production.

3 Data and methods

3.1 Digital government

This study uses the e-government development index as a tool to evaluate the degree of digital government development, building on previous research (Zhang and Xu, 2024). On the one hand, digital government is seen as the most recent phase of e-government growth. Its main goal is to create a collaborative and effective system for digital government operations, which will further modernize governance capacities and processes. The Electronic Government Development Index accurately captures the essential advancements in digital government development and precisely corresponds with the goals of digital governance that digital governments seek to achieve (Chen et al., 2025). On the other hand, the e-government development index's thorough and multifaceted assessment system offers a strong basis for gauging the capacities of digital government. This index assesses several important factors, such as internet services, talent assistance, and telecommunications infrastructure. Together, these elements make up the operational manifestation, technological underpinnings, and material basis of digital government activities, fully capturing a country's or region's total ability to advance digital governance. Therefore, rather of concentrating just on specific technological applications, the e-government development index measures the total efficacy of digital government creation at the macro level. It offers a thorough and reliable representation of the fundamental skills and state of development of digital governance.

3.2 Total factor productivity in forestry ecology

The SBM-GML model was used to quantify the green total factor productivity of forestry, drawing on previous studies (Jiang et al., 2020). Choose input indicators such as land, labor, capital, energy, and others; As the measure of economic gain among anticipated outputs, use gross forestry output; Refer to Xie et al.'s (2015) findings for the ecological benefit component. Provisioning, regulating, supporting, and cultural services are the different categories of forest ecosystem services. Grain correction coefficients, precipitation, and net primary production (NPP) data are used to change the ecological functional value, which is determined using the equivalent factor approach. The remaining three categories of system services are regarded as indications of ecological advantages as the gross forestry output value already includes the value of the material items supplied by supply services. In accordance with Wang et al.'s (2023) methodology, non-intended outputs are computed indirectly using metrics like the secondary forestry sector's output value, the overall industrial output value, and the industrial "three wastes" (solid waste, wastewater, and waste gas). The specific variable descriptions are shown in Table 1.

TABLE 1 Forestry ecological total factor productivity indicator system.

Norm	Indicator name	Representation
Input element	Land investment	Forest area
	Labor input	Number of employees in the forestry system
	Capital investment	Completed investment in forestry fixed assets
	Energy input	Energy consumption per unit of forestry output value
Expected outputs	Economic benefits	Gross forestry product
	Ecological benefits	Forestry ecological regulation services
		Forestry ecological support services
		Forestry ecological and cultural services
Non-expected outputs	Forestry waste gas production	Industrial SO_2 emissions* Forestry secondary industry output value/Industrial total output value
	Forestry solid waste output	Industrial solid waste generation rate* Forestry secondary industry output value/Total industrial output value
	Forestry wastewater output	Industrial wastewater discharge volume* Forestry secondary industry output value/Total industrial output value

3.3 Mechanism variables

3.3.1 New quality productivity

According to the study of Han et al. (2024), the creation of new-quality productive forces basically takes the form of a qualitative improvement in quality combined with the optimization and restructuring of production elements. Create a thorough index system for evaluating new, high-quality productive forces that takes into account both permeative and substantive factors. The ubiquitous aspects include new technology, production organization, and data elements; the substantive elements include new types of laborers, means of labor, and objects of labor. To compute weights and ascertain the overall amount of new-type productive forces, the entropy weight approach is utilized. While ubiquitous features emphasize the significance of organizational efficiency and technical innovation in boosting productivity, substantive factors directly reflect the basic resources used in the manufacturing process. Specifically, the system comprises multiple secondary indicators under these primary dimensions. For instance, 'new types of laborers' is proxied by the share of R&D personnel; 'new technology' is measured by R&D expenditure intensity and the number of patents; 'data elements' is reflected in internet penetration rate and related software business revenue. A full description of the indicator system and the entropy weight calculation process can be found in the source literature (Jiang et al., 2020). In order to increase forestry production efficiency and innovation capacities, new-type productive forces place a strong emphasis on both the improvement of resource elements and the driving role of technology and data.

3.3.2 Rationalization of the forestry industry structure

The degree of coordination and rationality among the many levels within the forestry sector is reflected in the rationalization of the industry's structure, which also serves as its optimization. The industrial structure hierarchy coefficient approach is used to systematically measure changes in the relative structure among the three forestry sectors, drawing on the work of Tang and Li (2017). Instead of only monitoring changes in the percentage of output value, this approach measures the degree of coordination of resource allocation among the primary, secondary, and tertiary forestry sectors as well as the effectiveness of resource usage. With a direct correlation to the degree of resource intensification and the achievement of encompassing forestry benefits, it offers a more sophisticated representation of the effectiveness of forestry factor allocation and the equilibrium of its internal structure. The core of this method is to assign differentiated weights to sectors based on their level in the industrial hierarchy, reflecting the structural height. The formula is applied as specified in the source study (Tang and Li, 2017):

$$F = \sum_{i=1}^{n} W_i Q_i \quad (n = 1,2,3) \tag{1}$$

F indicates the level of optimization in the forestry industry structure; W_i is the weight given to the primary, secondary, and tertiary sectors of forestry, with weights of 1, 2, and 3 attributed to these sectors, respectively (You et al., 2024); Q_i is a measure of the percentage of forestry's overall production value that comes from the primary, secondary, and tertiary sectors.

3.3.3 Advancement of the forestry industry structure

According to Kong et al.'s (2025) research, the upgrading of the forestry industry structure is the process of moving from a low-level to a high-level structure. Determined by dividing the overall forestry output value by the sum of the output values of the secondary and tertiary forestry sectors.

The transition of forestry production activities changing from a resource-dependent, low-value industry to a technology-intensive, high-value sector is clearly shown by this indicator. The trend toward the upgrading of the forestry industry is accurately characterized by the measurement of the percentage of secondary and tertiary industries, which effectively illustrates forestry's progress along the value chain—more specifically, the improvement of its technological sophistication, service attributes, and market competitiveness.

3.4 Control variables

Drawing on previous research (You et al., 2024; Wang et al., 2023), the following control variables are used for this study: (1) The percentage of primary forestry output value in total output value is a measure of the forestry industry's structure. The efficiency of allocating forestry resources will be impacted by changes in this parameter, which represents the structural level and economic dependency of the forestry sector. (2) Agriculture, forestry, and water affairs spending are indicators of government fiscal investment. These expenditures, which accurately reflect both financial assistance and policy direction in forestry development, are a crucial tool for the government to promote ecological transformation in forestry and improve production efficiency. (3) The intensity of fertilizer application, which has a direct effect on soil quality and the ecological environment's health, is a symbol of environmental pollution. Overuse of fertilizer pollutes the ecosystem, which hinders forestry's ability to grow sustainably. (4) Rural populations' educational attainment serves as a proxy for human capital investment. The workforce's technical expertise and inventiveness are reflected in educational attainment, and the forestry industry may modernize thanks to increased human capital. (5) The urbanization rate, which measures the degree of population concentration in urban regions, is a representation of the amount of urbanization. Different demands for land and resources are frequently brought about by faster urbanization, which has a big influence on how forestry resources are used and developed. The sophistication of regional information infrastructure and the dynamism of information flow are reflected in the level of informatization, which is determined by the ratio of postal and telecommunications business volume to regional GDP. The digital transformation and efficiency improvement of the forestry industry are indirectly impacted by this statistic. (7) The ratio of technology market transaction volume to gross domestic product indicates the degree of market development. The rate and efficacy of technical innovation, which is crucial for raising forestry production and ecological benefits, are directly influenced by the market's level of growth. Table 2 displays descriptive statistics for every variable.

3.5 Data sources

The E-Government Research Center of the Party School of the CPC Central Committee (National Academy of Governance) is the source of data on digital government. The EPS database, Wind database, China Forestry and Grassland Statistical Yearbook, and China Statistical Yearbook are the main sources of other variables. The study sample includes 30 Chinese provinces (not including Hong Kong, Macao, Taiwan, and the Tibet Autonomous Region) from 2015 to 2022, taking into account the availability of digital government data.

3.6 Research methods

The "curse of dimensionality" and estimation bias problems in conventional econometric models may arise because the effects of digital development frequently show nonlinear characteristics and because complex economic systems may make it impossible to fully account for all control variables. This is particularly pertinent in the context of forestry ecosystems, where productivity is influenced by a complex interplay of economic, social, and natural factors that are often difficult to quantify and may interact in nonlinear ways. Traditional parametric models (e.g., OLS, fixed effects) rely on strong functional form assumptions and struggle to flexibly account for these high-dimensional complexities, potentially leading to biased estimates. The accuracy of causal inference can be improved by utilizing the dual machine learning model's advantages in handling high-dimensional confounding factors and nonlinear interactions to effectively reduce estimation bias brought on by model specification errors. Specifically, the DML model does not require a pre-specified functional form for the relationship between control variables and the outcome, allowing it to more robustly capture the complex data-generating process inherent in forestry ecological systems. The model is implemented through a structured workflow: (1) random sample splitting into main and auxiliary sub-samples; (2) using machine learning algorithms in the auxiliary sample to flexibly estimate the conditional expectations of both the outcome and treatment variables given the controls; (3) estimating the causal coefficient in the main sample via a linear regression of the residualized outcome on the residualized treatment;

TABLE 2 Descriptive statistics.

Type	Variable meaning	Average value	Standard deviation	Minimum value	Maximum value
Dependent variable	Total factor productivity in forestry ecology	1.1840	0.9170	0.0817	7.5490
Explanatory variable	Digital government	83.3500	7.8920	61.2300	97.2300
Control variables	Forestry industry structure	1.4260	0.7480	0.7560	5.2970
	Government fiscal investment	667.8000	282.3000	110.3000	1359.0000
	Environmental pollution	0.0483	0.0236	0.0083	0.1190
	Level of human capital	7.9460	0.6320	5.8780	10.1100
	Urbanization rate	0.6270	0.1070	0.4290	0.8930
	Level of informatization	7.6570	0.7710	5.7620	9.0930
	Technology market development	0.0215	0.0323	0.0003	0.1910
Mechanism variable	New quality productivity	0.1090	0.1060	0.0150	0.6590
	Upgrading the forestry industry structure	0.5340	0.2350	0.0006	0.9240
	Optimization of the forestry industry structure	1.7220	0.3000	1.0010	2.3550

and (4) repeating the process via cross-fitting (e.g., 5-fold) and averaging the estimates to ensure robustness and efficiency. Our benchmark specification employs a neural network algorithm, a 1:4 sample split ratio, and 5-fold cross-fitting. In order to empirically investigate the effect of digital government development on the total factor productivity of forestry ecosystems, this article uses a dual machine learning model. Basic model construction as shown in Equations 2, 3:

$$G_{it} = \theta_0 D_{it} + g\left(X_{it}\right) + U_{it} \tag{2}$$

$$\mathrm{E}\left(\mathrm{U}_{\mathrm{it}} \middle| \mathrm{D}_{\mathrm{it}}, \mathrm{X}_{\mathrm{it}}\right) = 0 \tag{3}$$

I and t stand for province and year, respectively; D_{it} stands for digital government; θ_o is the treatment coefficient; X_{it} is the set of control variables; U_{it} is the error term with a conditional mean of zero; and G_{it} is the total factor productivity of forestry ecosystems. In accordance with the methodology of Xie et al. (2024), an auxiliary regression is constructed using Equations 4, 5 below to ensure the unbiasedness of the treatment coefficient estimator:

$$\mathrm{D}_{\mathrm{it}} = \mathrm{m}\left(\mathrm{X}_{\mathrm{it}}\right) + \mathrm{u}_{\mathrm{it}} \tag{4}$$

$$\mathrm{E}\left(\mathrm{u}_{\mathrm{it}} \middle| \mathrm{X}_{\mathrm{it}}\right) = 0 \tag{5}$$

The regression function of the treatment variable on the high-dimensional control variables is represented by m (X_{it}) in the equation, while the error term with a conditional mean of zero is shown by μ_{it}.

4 Empirical analysis

4.1 Benchmark regression analysis

To verify the effect of digital government development on the total factor productivity of forestry ecosystems, this study uses a dual machine learning model combined with neural network techniques and 5-fold cross-validation with a 1:4 sample division ratio. The matching empirical data are shown in Table 3. According to Model (1), the results are substantially positive at the 1% level when province and year fixed effects and the first-order terms of control variables are taken into account for the full sample range. This illustrates how the growth of digital governance has a major beneficial effect on raising the overall factor productivity of forestry ecosystems. Model (2) expands on this basis by adding quadratic terms for control variables in regression analysis. The coefficient for digital government is still substantially positive, suggesting that the growth of digital government successfully raises the productivity of forestry ecological total factors. In particular, forestry ecological total factor production rises by 0.3135 units for every unit growth in digital government development. Thus, hypothesis H1 is confirmed.

4.2 Robustness tests

This work performs robustness tests by decreasing the sample size, changing the sample partitioning ratio, and swapping out the algorithm in order to verify the accuracy of the benchmark regression findings. First, all variables were cut at the 1 and 5% levels prior to and following the outliers, respectively, and reexamined because outliers in the sample could affect the research findings. The regression results are displayed in Table 4's Column (1). The robustness of the benchmark regression results is demonstrated by the positive and significant estimated coefficients. Second, by changing the sample split ratio from the previous 1:4 to 1:2 and 1:6, the robustness of the model test results is reexamined below in order to reduce estimation bias brought on by model misspecification. The particular outcomes are displayed in Table 4's Column (2). The correlations for digital government development on forestry ecological total factor production remained significantly positive at the 1% level even after correcting for the sample split ratio. This suggests that changing the sample split ratio has no appreciable effect on the findings of the study. Lastly, this study substituted gradient boosting for the previously preset neural network algorithm in order to minimize algorithm-induced mistakes and prevent model algorithm bias from influencing

TABLE 3 Benchmark regression.

Variable name	(1)	(2)
	Total factor productivity in forestry ecology	Total factor productivity in forestry ecology
Digital government	0.0839***	0.3135***
	(0.0155)	(0.0680)
Control variable single term	Controlled	Controlled
Control variable quadratic term	Uncontrolled	Controlled
Year fixed effect	Controlled	Controlled
Provincial fixed effects	Controlled	Controlled
Observed values	240	240

*, ** and *** denote significant at the 10, 5 and 1% statistical levels, respectively.

the findings. The findings are displayed in Table 4's column (3). The result that digital government development greatly increases forestry ecological total factor productivity remains true even after altering the algorithm, as seen by the regression coefficients utilizing gradient boosting remaining significantly positive.

It is important to note that while the direction of the influence remains consistent, the magnitude of the estimated coefficients varies across different specifications. Specifically, the estimate under the 1:2 sample partition ratio (Column 3 in Table 4) is noticeably larger than the benchmark. This fluctuation is attributable to the inherent trade-offs in the Dual Machine Learning framework. A 1:2 split ratio significantly reduces the training sample size for estimating nuisance parameters, which can increase the variance of the final estimator, particularly in smaller datasets ($N = 240$). Despite these numerical variations, the coefficients in all robustness checks consistently maintain a positive sign and statistical significance. This consistency confirms that the core conclusion of this study—that digital government empowers forestry ecological TFP—is robust to model selection and sample splitting strategies, even if the precise point estimate exhibits sensitivity to the algorithm's hyperparameters.

4.3 Endogeneity treatment

The instrumental variables technique is used to reduce the risk of endogeneity problems because it is impossible to fully account for every element that could affect the overall factor productivity of forestry ecosystems. A dual machine learning partial linear instrumental variables model is built for analysis using Zhang and Li's (2023) methodology. See Equations 6, 7, where Z_{it} is an instrumental variable for D_{it}.

$$G_{it} = \theta_0 D_{it} + g\left(X_{it}\right) + U_{it} \tag{6}$$

$$Z_{it} = m\left(X_{it}\right) + u_{it} \tag{7}$$

When choosing instrumental variables, we followed Huang et al.'s (2019) advice. First, the "digital government lagged by one period" is chosen as an instrumental variable in this paper because it satisfies the criteria for instrumental variable selection by having a strong correlation with the current state of digital government development but having no direct impact on the overall factor productivity of forestry ecosystems. Second, as an additional instrumental variable, this paper creates the "interaction term between the number of post offices in 1984 and the previous year's digital government variable." On the one hand, historical infrastructure's spatial distribution usually has long-term exogenous consequences on current economic activity. As a historical variable, the quantity of post offices in 1984 indicates the degree of growth of postal and telecommunications infrastructure in the early 1980s, which at the time represented the building of digital infrastructure. Post offices' network and services established the groundwork for later developments in digital government. Consequently, the number of post offices and the development of digital government have a historical cumulative relationship that shows a strong correlation and meets the correlation criteria in instrumental variable creation. On the other hand, forestry ecological total factor productivity is not directly impacted by the interaction term between the 1984 number of post offices and the digital government variable from the prior year. Rather, it satisfies the instrumental variable's exogeneity assumption by indirectly influencing the development of digital governance. The benchmark regression results are further supported by Table 5, which illustrates that the promotional effect of digital government development on forestry ecological total factor production is still valid once endogeneity difficulties are resolved.

4.4 Analysis of transmission mechanisms

4.4.1 Mediating effect

The development of digital government does, in fact, help to increase the overall factor productivity of forestry ecosystems, according to earlier studies. The specific focus of this research is on how the growth of digital government encourages increases in the total factor productivity of forestry ecosystems. According to theoretical analysis, there are three possible explanations for the evolution of forestry ecosystem total factor productivity: the influence of digital government development on new-type productive forces, as well as the modernization and simplification of forestry industrial structures. In order to achieve this, use Jiang Ting's mechanism testing framework (Boat, 2022), Regression analysis with a two-step mediation effect was performed. Table 6 displays the regression findings.

The estimation results using new-type productive forces as the institutional variable are shown in Column (1) of Table 6. According to the findings, the coefficient for digital government is noticeably positive, indicating that the development of digital government can successfully boost the expansion of new productive forces and raise the overall factor productivity of forestry ecosystems. Thus, hypothesis H_2 is confirmed. Digital government development significantly improves forestry industrial structure rationalization, which in turn improves forestry ecological total factor productivity, according to estimation results presented in Table 6 column (2) with forestry industrial structure rationalization as an intermediate variable. Thus, hypothesis H_3 is confirmed. The estimation results employing upgrading of the forestry industrial structure as an intermediate

TABLE 4 Robustness test.

Variable name	(1) Reduced sample		(2) Modify the sample partitioning ratio		(3) Change algorithm
	Shrinkage 1%	Shrinkage 5%	1:2	1:6	Gradient boosting
Digital government	0.3136***	0.2942***	1.9187***	0.4673***	0.0173*
	(0.0682)	(0.0678)	(0.1580)	(0.0917)	(0.0091)
Control variable single term	Controlled	Controlled	Controlled	Controlled	Controlled
Control variable quadratic term	Controlled	Controlled	Controlled	Controlled	Controlled
Year fixed effect	Controlled	Controlled	Controlled	Controlled	Controlled
Provincial fixed effects	Controlled	Controlled	Controlled	Controlled	Controlled
Observed values	240	240	240	240	240

Robust standard errors are in parentheses. *, ** and *** denote significance at the 10%, 5%, and 1% levels, respectively.

TABLE 5 Endogenous test.

Variable name	(1) IV: Digital Government Phase One Lag	(2) IV: Interaction term constructed between 1984 post office figures and the previous year's government variable
Digital government	0.4990***	0.6326***
	(0.0537)	(0.0286)
Control variable single term	Controlled	Controlled
Control variable quadratic term	Controlled	Controlled
Year fixed effect	Controlled	Controlled
Provincial fixed effects	Controlled	Controlled
Observed values	240	240

*, ** and *** denote significant at the 10, 5 and 1% statistical levels, respectively, with robust standard errors in parentheses.

TABLE 6 Mechanism test.

Variable name	(1) New quality productivity	(2) Optimization of the forestry industry structure	(3) Upgrading the forestry industry structure
Digital government	0.6271***	0.7575***	0.4987***
	(0.0290)	(0.1034)	(0.0537)
Control variable single term	Controlled	Controlled	Controlled
Control variable quadratic term	Controlled	Controlled	Controlled
Year fixed effect	Controlled	Controlled	Controlled
Provincial fixed effects	Controlled	Controlled	Controlled
Observed values	240	240	240

Robust standard errors are in parentheses. *, ** and *** denote significance at the 10%, 5%, and 1% statistical levels, respectively.

variable are shown in column (3) of Table 6. Digital government development can improve forestry industrial structure upgrading and, consequently, increase forestry ecological total factor productivity, as indicated by the predicted coefficient for digital government on forestry industrial structure upgrading being highly positive. Thus, hypothesis H_4 is confirmed. Looking back at its beginnings, we can see that the development of digital government has boosted new-type productive forces by transforming forestry production methods through the development of intelligent platforms, information infrastructure, and data-driven decision support systems. By reducing resource waste and encouraging efficient resource utilization, the implementation of these new-type productive forces—like intelligent forest patrols and precision monitoring technologies—has increased the total factor productivity of forestry ecosystems. Second, by precisely allocating resources and providing policy direction, the digital government has streamlined the forestry sector. The government can improve resource consumption efficiency and optimize resource distribution by utilizing big data analytics. At the same time, the digital government's policy orientation has encouraged industrial restructuring, directing businesses toward low-carbon and green transformation while increasing the forestry sector's total production efficiency. Lastly, by improving the technological sophistication and added value of forestry products, expanding the industrial chain, streamlining the layout of industries, and promoting the sector's green and intelligent development, the digital government has advanced the upgrading of the forestry industry structure. This has increased the growth of total factor production in forestry ecosystems by strengthening sustainability and increasing industrial efficiency. The growth of digital government has improved ecological conservation and the overall efficiency of forestry production through the synergistic impacts of these three paths, increasing the total factor productivity of forestry ecosystems.

These empirically verified mechanisms delineate a clear policy pathway for leveraging digital government as a central driver of high-quality forestry development. They demonstrate that digital government is not merely an administrative tool but a transformative force that acts upon the core dimensions of high-quality growth: it injects momentum through technological innovation (new quality productive forces), enhances efficiency through optimized organization (industrial structure rationalization), and creates new value through industrial transformation (industrial structure upgrading). The synergistic impacts of these three paths illustrate how digital government development can systematically improve both ecological conservation and the overall efficiency of forestry production, thereby operationalizing the strategic goal of high-quality development in the forestry sector.

4.4.2 Modulating effects

The moderating mechanism found in the theoretical study is empirically tested in Table 7. As a moderator variable, an interaction term between the digital economy and digital governance is created and added to the baseline regression model. The predicted moderating effect coefficient, according to the regression results, is 0.2779, which is statistically significant at the 95% confidence level. This supports Hypothesis H5 by indicating that the digital economy has a positive moderating influence on the process by which digital governance raises the total factor productivity of forestry ecosystems. In particular, the efficacy of digital government construction is further increased at high levels of digital economic development. The enhancement of total factor production in forestry ecosystems is mostly driven by the two factors working in concert. By encouraging the use and innovation of information and intelligent technology, the digital economy optimizes production processes and resource allocation in the forestry sector while also raising product value-added and production efficiency. By supporting policies, creating digital platforms, and facilitating data sharing, digital government in turn offers strong support for the digital economy. The widespread use of digital technology and efficient resource allocation made possible by the synergistic connection between these two factors efficiently increase the forestry industry's overall advantages and promote both ecological and economic development. Therefore, the digital economy not only supports the high-quality and sustainable growth of the forestry sector, but also magnifies the role of digital government development in boosting forestry ecological total factor productivity.

TABLE 7 Moderating effects.

Variable name	Total factor productivity in forestry ecology
Digital Government *digital economy	0.2779**
	(0.0834)
Control variable single term	Controlled
Control variable quadratic term	Controlled
Year fixed effect	Controlled
Provincial fixed effects	Controlled
Observed values	240

Robust standard errors are in parentheses. *, ** and *** denote significance at the 10%, 5%, and 1% statistical levels, respectively.

4.5 Heterogeneity test

Because of its size, China has large regional differences in terms of resource endowments and economic growth stages. The impact of digital government activities on the total factor productivity in forestry ecosystems may be influenced by this heterogeneity. As a result, this study does a heterogeneity analysis based on two dimensions: the intensity of forest resource endowment and the degree of economic development.

4.5.1 Heterogeneity in economic development levels

We separated the sample areas into economically developed and economically underdeveloped groups for regression analysis, and then compared the average regional GDP of the sample areas from 2015 to 2022 to quantify their economic foundations in order to investigate the effects of economic development heterogeneity. Table 8 (1) and (2) present the findings. According to the results, the predicted coefficients for economically developed regions are notably positive, indicating that the growth of digital governance considerably raises the forestry ecosystems' total factor productivity. However, there is no discernible impact on economically deprived areas. The most likely explanation is that economically developed areas have larger economic capacities, more sophisticated digital infrastructure, and higher degrees of technical application. Digital government initiatives can greatly increase the efficiency of forestry production and resource consumption by offering accurate policy support, optimizing resource allocation, and easing information sharing. Therefore, it is evident that the growth of digital governance in economically developed areas raises the overall factor productivity of forestry ecosystems. However, the development of digital government has not been able to reach its full potential in economically poor countries because of comparatively slow digital infrastructure development and lower levels of technology deployment. As a result, it has no discernible positive impact on the overall factor productivity of forest ecosystems. This discrepancy illustrates how economic development levels affect how well digital government is built.

4.5.2 Heterogeneity in forest resource enrichment

Larger forest lands typically encourage the forestry industry's scaled and diversified development, which improves the overall ecological advantages and efficiency of resource utilization. The average yearly forest area throughout the study period was used to classify regions into forest-rich and forest-poor areas based on this

TABLE 8 Heterogeneity test.

Variable Name	Level of economic development		Forest resources	
	(1) Advanced group	(2) Less developed group	(3) Enrichment group	(4) Deprivation group
Digital government	1.3612***	−0.0161	0.5413***	0.1576
	(0.1465)	(0.1573)	(0.1237)	(0.1071)
Control variable single term	Controlled	Controlled	Controlled	Controlled
Control variable quadratic term	Controlled	Controlled	Controlled	Controlled
Year fixed effect	Controlled	Controlled	Controlled	Controlled
Provincial fixed effects	Controlled	Controlled	Controlled	Controlled
Observed values	240	240	240	240

Robust standard errors are in parentheses. *, ** and *** denote significance at the 10%, 5%, and 1% statistical levels, respectively.

principle and data from the National Bureau of Statistics. To determine whether digital government activities had varying effects on the total factor productivity of forestry ecosystems, degrees of forest resource richness were compared. The findings are shown in columns (3) and (4) of Table 8. The region with the most forest resources passed the significance test with regard to regression coefficients, but the region with the fewest forest resources did not. The tenable reasoning is that by maximizing resource allocation and boosting management effectiveness, digital government development can dramatically raise the total factor productivity of forestry ecosystems in areas with an abundance of forest resources. Digital government may play a critical role in resource conservation, forest management, and ecological monitoring, hence boosting the usage efficiency and ecological advantages of forest resources. The forestry businesses in these areas have a stronger demand for digital transformation. On the other hand, the influence of digital government development on forestry ecological total factor productivity does not meet the importance level in areas with limited forest resources due to the limited nature of the resources and the comparatively smaller impact of the development. This suggests that the expansion of digital government in these regions does not considerably increase the efficiency of forestry production. According to this research, in order to improve results in areas with limited forest resources, digital government development may need to be paired with other industrial transformation initiatives and resource supplementation plans.

4.6 Discussion: relationship with existing literature

The empirical results of this study are closely connected with, and extend, the existing literature on digital governance and total factor productivity. First, the benchmark DML estimates show that digital government development significantly improves forestry ecosystem TFP. This finding is consistent with previous evidence that digital governance and related digital technologies can enhance total factor productivity by reducing transaction costs, improving public service efficiency and optimizing resource allocation in other sectors of the economy (Qi, 2024; Su et al., 2024; Lun and Liu, 2024). Our contribution is to document a similar productivity-enhancing effect in a highly ecological and externality-intensive sector such as forestry, thereby filling the research gap noted in the introduction that forestry ecosystems have received limited attention in the digital governance literature (Lun and Liu, 2024; Mou et al., 2025; Zeng et al., 2025; Peng and Peng, 2025; Lü et al., 2025).

Second, the mechanism tests provide empirical support for the theoretical channels proposed in Section 2 and resonate with existing studies on new quality productive forces and industrial restructuring. The positive transmission from digital government to forestry ecosystem TFP through new-type productive forces is in line with the view that data-driven innovation, intelligent equipment and high-skill human capital constitute an emerging “new quality” productivity base in China’s real economy (Han et al., 2024). Likewise, the mediating role of both the rationalization and upgrading of the forestry industrial structure is consistent with prior work highlighting that structural optimization and movement towards higher value-added segments are key drivers of green TFP in resource-based and ecological industries (Shi et al., 2025; Tang and Li, 2017).

Third, the moderating and heterogeneity results relate to the growing literature on the digital economy and regional disparities. The positive moderating effect of the digital economy suggests that digital government and the digital economy form a mutually reinforcing ecosystem, in which digital infrastructure and market-oriented digital applications amplify the productivity effects of digital governance (You et al., 2025; You et al., 2024). The stronger effects observed in economically developed and forest-rich regions, together with statistically insignificant effects in less developed or resource-poor regions, also echo the “digital divide” discussion: without sufficient economic capacity, digital infrastructure and resource endowment, the potential productivity gains of digital government in ecological sectors are difficult to fully realize.

5 Conclusions and policy recommendations

5.1 Conclusion

Using a dual machine learning model, this paper empirically analyzes the impact of digital government development on forestry ecosystem total factor productivity in 30 Chinese provinces (2015–2022) and examines its underlying transmission mechanisms. The following conclusions are drawn from the findings: First, the growth of digital government greatly raises forestry ecosystems' overall factor production. The results of the robustness and endogeneity tests support this conclusion. Second, the mechanism analysis shows that digital government improves forestry ecological TFP in a number of ways. By encouraging new types of productive forces, increasing the sophistication of forestry industrial structure, and streamlining forestry industrial structure, digital government development increases forestry ecological TFP. The study also reveals that the digital economy has a positive moderating influence on this process: the more developed the digital economy, the more strongly digital government development promotes forestry ecological TFP. Third, the influence boundaries are further refined by heterogeneity analysis, which shows that the positive impact of digital government on forestry ecological TFP increases with the amount of regional economic development and forest resource endowment.

5.2 Recommendations

Building directly upon the empirical findings of this study, which confirm the significant positive impact of digital government and its transmission through new quality productivity, industrial rationalization, and industrial upgrading, the following policy recommendations are proposed to channel digital government development into concrete strategies for high-quality forestry growth:

(1) To strengthen the foundational framework for increasing the total factor productivity of forestry ecosystems, advance the development of digital government.

This recommendation directly addresses the baseline finding that digital government development is a significant driver of forestry ecological TFP. The policies outlined below are designed to amplify this core effect. Governments at all levels should give priority to digital government activities as a key component of modernizing forestry, given the substantial contribution that these projects provide to increasing the total factor productivity of forestry ecosystems. This calls for more funding and ongoing reform initiatives. In particular, improving digital infrastructure in the forestry industry should be prioritized. This entails building big data centers and cloud computing platforms, extending the coverage of 5G communication base stations, putting IoT sensors throughout forest regions, and setting up high-precision remote sensing satellite networks. These steps will guarantee thorough, accurate, and up-to-date forestry data collection, transmission, and storage. Simultaneously, in order to lower the institutional transaction costs for forestry operators and boost market vitality, we must constantly optimize digital government service processes, expedite approval processes connected to forestry, and encourage "one-stop online services" and "mobile services." Moreover, departmental obstacles and information silos should be dismantled by establishing a single, open platform for exchanging forestry data. Data from departments including natural resources, water conservation, environmental protection, and meteorology will be connected and applied more effectively as a result, supporting scientific decision-making and accurate forestry management.

(2) Increase institutional innovation to produce new, high-quality productive forces that will optimize and upgrade the structure of the forestry industry.

According to the mechanism analysis of this study, digital government improves forestry ecosystems' total factor production in a number of ways, such as by creating new, high-quality productive forces and by developing and streamlining forestry industrial structures. Policymakers must thus combine their supply-side and structural-side initiatives. First, increase the rate at which forestry is developing new, high-quality productive forces. Give top priority to advancing important forestry core technologies, including smart patrol systems, forestry robotics, intelligent breeding, forest tree gene editing, and new biomass materials. Encourage the thorough integration of forestry production with these state-of-the-art technologies. Create a special research fund to promote close cooperation between industry, academia, research institutes, and end users. This would speed up the conversion of scientific and technological advancements into useful applications and serve as a hub for the development of new forestry productivity. Second, encourage the forestry industry's structure to be more rational. To accurately assess input–output efficiency and synergistic links among primary, secondary, and tertiary forestry businesses and direct resource flows toward more lucrative and environmentally sustainable segments, take advantage of digital government's data insights capabilities. To avoid blind expansion and unproductive investment, for example, use digital platforms to guide assessments of forest site suitability, improve the selection of tree species and stand structure, and achieve precise, intensive usage of forest resources. Third, promote the modernization of the structure of the forestry sector. Assist the forestry industry in shifting from traditional primary goods like timber harvesting to newer sectors like eco-tourism, green forest product manufacture, high-value deep processing, forest carbon sink management, and forest wellness. The establishment of digital trading platforms for forest ecological goods by digital government efforts can make it easier to quantify, verify rights, and trade forest carbon sinks and ecosystem services on a market basis. This will open up more avenues for forestry's value to be realized and draw more social capital investment into the advanced growth of the sector.

(3) Boost the digital economy's level and unleash the digital government's multiplier impact to increase forestry's overall factor productivity.

The development of digital government should be tightly linked with regional digital economic growth in order to generate synergistic effects, given the beneficial regulatory influence of the digital economy on the total factor productivity of forestry ecosystems through digital government empowerment. First, raise the degree of regional digital economic development in its whole. Encourage the use of digital technologies across a wider range of industries, such as services, industry, and agriculture. Develop digital talent, enhance the development of digital infrastructure, and create a thriving digital industrial environment. In addition to offering a better working environment for digital government, this will also give the digital transformation of forestry greater access to technology, people resources, and markets. Second, improve how the digital economy and digital government connect and integrate. In order to manage resources and provide public services, digital government projects should be encouraged to work more closely with businesses in the digital economy. Establish professional services and market-based mechanisms to collaborate on the development of digital forestry solutions. This will improve digital government's knowledge and service skills and create a positive feedback loop in which the government gives direction, the market leads, and technology provides strong support.

(4) Use unique tactics to encourage regional forestry's coordinated digital growth.

According to the heterogeneity analysis, locations with abundant forest resources and economically developed regions see a greater promotional effect of digital government on the total factor productivity of forestry ecosystems. This suggests that rather than taking a one-size-fits-all approach, policymaking should be customized to local circumstances. First, it is important to support the pioneering and experimentation of economically developed and forested areas. Assist these sectors in developing new models, using technology, and investigating regulations for forestry provided by digital government. Create smart forestry pilot and demonstration zones, then share their best practices and successful experiences with additional places. Second, the emphasis should be on providing targeted support and bolstering basic capacities in places with limited forest resources and economically disadvantaged regions. Addressing digital infrastructure shortages, improving forestry workers' digital literacy, and creating unique forestry enterprises in line with local resource endowments should be the top priorities for digital government development in these areas. Policies might boost funding, giving priority to the development of useful digital technologies and the maintenance of fundamental digital infrastructure. In order to ensure that the advantages of digital government are distributed fairly, encourage endogenous growth momentum, and progressively close the digital divide, cooperative mechanisms for ecological compensation and digital technology support with developed regions should be investigated.

5.3 Limitations and future research

Despite the contributions of this study, there are several limitations that provide opportunities for future research.

This study employs a macro-level e-government index as a proxy for digital governance, which, while validated, may not fully capture sector-specific digitalization within forestry or sub-provincial variations in implementation

This measurement approach is inherently linked to the methodological scope of our study. Our dual machine learning (DML) model is primarily designed to address high-dimensional confounding and nonlinear relationships in the core causal pathway. However, this framework does not explicitly model two other potentially important dimensions: spatial spillover effects and dynamic adjustments. Consequently, our current design does not account for whether digital government development in one province might influence forestry ecological TFP in neighboring regions (spatial effects), or how the productivity impacts evolve over multiple time periods (dynamic effects). Future research should aim to develop more granular, sector-specific digital governance indicators. Furthermore, extending the analytical framework to incorporate spatial econometric models (e.g., Spatial Durbin Model) or dynamic panel data models (e.g., GMM estimators) would be a valuable direction to capture these complex interdependencies and temporal dynamics, thereby providing a more comprehensive understanding.

5.3.1 Causal inference and endogeneity

While the dual machine learning (DML) approach helps control for confounding variables, residual endogeneity and dynamic feedback loops may still affect causal interpretation. Future studies could utilize natural experiments, staggered DID models, or panel-VAR/LP techniques to better isolate causal mechanisms. Furthermore, while the mechanism analysis within the DML framework provides a robust initial test, future research could seek to further validate these mediating pathways by developing and applying specialized causal mediation analysis techniques that are fully compatible with high-dimensional confounding controls.

5.3.2 Ecological and spatial generalization

The current study focuses on forestry ecological TFP at the provincial level, and its generalizability to other regions or countries may be limited. Future research could explore intra-provincial heterogeneity or focus on finer spatial scales such as cities or forest management units to capture localized variations in governance and ecological outputs. Furthermore, research should explicitly model spatial dependence by employing spatial econometric techniques to investigate potential spillover effects, where digital government development in one province may influence forestry outcomes in neighboring regions, thereby capturing the regional linkage effects that lie beyond the scope of our current analysis.

5.3.3 Scalability and cross-national application

This study is grounded in the Chinese context, which features a unique state-led governance model. An essential direction for future research is to explore the scalability and adaptability of digital government applications in forestry beyond China. Future studies could employ comparative case studies to investigate how digital government models, particularly those proven effective in China, can be adapted to different institutional environments (e.g., market-driven systems, community-based forest management regimes), levels of economic development, and forest tenure systems. This line of inquiry would be crucial for validating the universal mechanisms and identifying the context-specific prerequisites for successfully transferring digital governance solutions in forestry on a global scale.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

HC: Supervision, Writing – original draft, Data curation, Methodology, Conceptualization. CZ: Writing – original draft, Software, Validation. ML: Formal analysis, Writing – original draft, Investigation. SX: Resources, Writing – original draft. BD: Writing – review & editing, Visualization. LC: Visualization, Writing – review & editing, Writing – original draft.

Funding

The author(s) declared that financial support was received for this work and/or its publication. This work was funded by the National Social Science Fund [Grant No. 19BGL087] and Fujian Province Social Science Planning Youth Project [Grant No. FJ2022C096].

Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The reviewer BX declared a shared affiliation with the authors HC, CZ, ML, SX, and BD to the handling editor at time of review.

Generative AI statement

The author(s) declared that Generative AI was not used in the creation of this manuscript.

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