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A digital twin framework for innovating rural ecological landscape control

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Abstract

Background Because cities prioritize economic development and face ecological space and resource constraints, the development of rural areas, which have untapped potential, should receive increased attention. Consequently, rural ecological landscapes should be constructed through the control of land use types and quality to fully ensure the sustainable development of urban and rural ecosystems. The digital twin is a philosophy and a methodology that connects the digital and physical realms, facilitating realistic and dynamic mapping simulations of the real world. This capability offers valuable insights for digital decision-making, maintenance, and optimization of rural ecological landscapes. Given the digital transformation of rural ecological landscape control, this paper proposes a rural intelligent control approach based on the digital twin concept and new technology.

Methods Five components of the rural ecological landscape digital twin framework are selected to collectively facilitate the monitoring and analysis of rural conditions, formulate strategic solutions, implement management and control behaviors, and enhance participant interaction. The method includes three steps: mapping and fusing information, constructing and managing a database, and constructing a digital platform. Data mining and spatial fusion are performed through targeted mapping methods, and Oracle and ArcGIS SDE are utilized for database construction and fused data management. The twin platform is generated via HTML, desktop application development and geographic information system development technologies using a distributed system as the core.

Results Based on multiple case studies, our platform efficiently gathers system information on rural ecological landscapes using a twin model. Through evaluation and analysis, it determines landscape governance zones, adjusting them based on land use conditions. The platform refines control schemes with feedback from diverse users, ensuring effective control in various scenarios. Its key advantages include high development efficiency, flexible access, and smooth cross-platform integration. Although implemented in rural China, the proposed digital twin framework is applicable to any rural area requiring ecological landscape digital control.

Conclusions The value of the platform lies in its powerful information processing capability, overcoming the limitations of time and space and enabling the presentation and integration of fictional scenes Thus, the platform provides a reference for the digital transformation of rural ecological landscape control.

Keywords Digital twin, Framework, Rural ecological landscape, Control

Introduction

Human transformation of the Earth system has altered more than three-quarters of the planet's biomes into anthropogenic biomes [10]. In the past, the demand for resources led to the persistent encroachment into natural land areas and the continuous degradation of ecological functions, consequently, severe ecological pressure

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has been placed on urban and rural environments [45]. Given that cities prioritize economic development and face constraints related to ecological space and resources, more attention should be given to the development of rural areas, which are often broad and have untapped potential. Consequently, a rural ecological landscape should be constructed through the control of land use type and quality to fully ensure the sustainable development of urban and rural ecosystems.

The rural ecological landscape is an important infrastructure component that supports the improvement of the rural ecological environment, the supply of ecological products, and the coordinated development of urban and rural areas [21, 22]. From the perspective of landscape ecology, the rural ecological landscape is regarded as the fundamental ecological basis for the formation of the rural landscape and is the resource background for performing economic and social activities throughout the countryside. Population growth exacerbates the severe conflict between land scarcity and surplus labor. On one hand, the proliferation of artificial structures contributes to increased hardened land. On the other hand, farmers expand cultivated areas by converting extensive forests and meadows into sloping farmland [26, 56]. Consequently, the rural ecological landscape in China has experienced gradual deterioration [47]. Recognizing this trend, China has placed emphasis on ecological priorities and heightened its attention to the management of rural ecological landscapes in recent years [36].

As human society has entered the fourth industrial revolution, the digital transformation of the world economy is accelerating, and the digital transformation of rural areas is imminent. To solve this problem, Dutch scholars established the Rural Life Laboratory (RLL) to support the digital transformation process in rural environments [29]. They considered how to achieve transformations from five dimensions: information and communication technology (ICT) and infrastructure, management tasks, users and partners, research, and methods [14]. These dimensions are rapidly developing in the EU and European countries, and the European Life Laboratory Network has gradually formed [49]. In China, digital villages are undergoing endogenous agricultural and rural modernization development and transformation processes accompanied by the application of networking, informatization, and digitalization in agricultural and rural economic and social development, and farmers' modern information skills are improving [46]. The focus of rural digital transformation work involves the construction of information infrastructure, public support platforms, digital application scenarios, operation management, and system security. Expanding reform and innovation-driven approaches is a priority, giving full play to the leading role of a new generation of information technology based on innovative systems, mechanisms, and models. From this perspective, relying only on one or a simple collection of several digital technologies may not support the needs of digital management and control. It is necessary to construct a system implementation pathway and establish corresponding technical logic. The keys to digital transformation include reshaping traditional management and control processes and models based on sound infrastructure, building a digital operating environment and application scenarios, connecting all participants, and improving the accuracy and efficiency of management and control.

Based on this conceptual approach, the digital twin, as an emerging tool, has gradually displayed advantages in various scenarios. As a philosophy that closely links the digital and physical worlds, the digital twin approach is often used to carry out highly realistic and dynamic mapping and simulations of the real world based on digital technology [7]. This process can provide in-depth insights for decision-making, maintenance, optimization, etc., meet the needs of rural ecological digital management and control, and provide a path for technological integration and application to achieve related goals.

At present, digital twins are widely used in agricultural production. Digital twin systems are used to synchronously map the greenhouse environment, control plant growth, and manage the surrounding environment [3]. Such applications aim to improve the agricultural production efficiency, optimize plant yield, and enhance product quality. In addition, some scholars have focused on the high realism of digital twins and utilized them to support the construction of digital simulation models and scenarios for rural tourism and exploration [11, 27]. However, their use in the protection and construction of rural ecological landscapes is still in its infancy. The Agricultural Research Center of the School of Life Sciences of the Technical University of Munich (TUM) has established a digital twin of the agricultural landscape. This has involved integrating interdisciplinary data from different sources into the information system and mapping the complex agricultural landscape system to a scalable information model, unrelated to a specific application, for the first time through the development of LandModel, which serves as a digital twin [23]. Most practical projects and scholarly research in China have focused on the morphological digitization of rural ecological landscapes, with emphasis on constructing digital models and multidimensional expressions [50, 58], as well as quantifying and spatially analyzing landscape characteristics [6].

Despite the fact that the research and application of digital twins are just emerging, China presents a high level of interest and attention to digital twins. With the launch of China's "14th Five-Year Plan", which proposes the need to accelerate digital development and build a digital China, the pace of smart city and digital twin city construction across the country has accelerated. The China Academy of Information and Communications Technology has published three white papers on digital twins and promote the rapid development of urban information modeling (CIM)- and building information modeling (BIM)-related technologies, industries, and applications, thereby aiding in the construction of digital twin cities [51, 53]. Rural areas in China boast a well-developed information and communication infrastructure that is characterized by high network penetration, facilitating business activities driven by digital technology [16, 30]. In addition, numerous comprehensive information platforms have emerged to support various rural control functions, including township and village government websites, information service stations, and agriculture-related websites and e-commerce portals [44]. The construction of China's integrated urban–rural planning platform has resulted in the establishment of extensive ecological and land resource databases [42, 52, 57]. The existence of the above infrastructures, databases and platforms have all greatly facilitated and supported the implementation of digital twins in China, but there are still some limitations in the actual implementation. Such as the lack of construction of a digital model for all elements and lack of establishment of a specialized platform [9]. The digital twin path of the rural ecological landscape environment is a topic that requires further research and discussion.

Therefore, this study innovatively proposes a digital twin conceptual framework for rural ecological landscapes that contains relevant business scenarios, components and contents, aiming to improve the control efficiency and accuracy of rural ecological landscapes. The challenges are (1) how to express the characteristics of rural ecological landscapes realistically; (2) how to construct a multi-dimensional twin model in the virtual earth; and (3) how to construct a digital twin platform that can realize digital control with the help of the twin model. In this study, we map the rural ecological landscape system information through various digital means, construct a database, build a multi-module distributed platform under hybrid architecture, generate a four-dimensional rural twin model in the platform that can be used for display, and apply it to multiple scenarios of digital control. The twinning framework seamlessly integrates the control process, connecting all involved stakeholders to enhance the scientific, precise, and efficient nature of control. Given China's heightened ecological landscape pressures and the urgent need for intelligent control in rural areas, coupled with a solid foundation in digitalization and high implementation feasibility, China stands as an ideal region for the framework proposed in this thesis. The proposed framework is applied to construct a mapping model and platform in rural areas in China, with the goal of exploring the actual value of the platform.

The concept of the digital twin in rural ecological landscapes

Service scenarios involving digital twins

The rural ecological landscape exhibits complex and dynamic characteristics, coupled with diverse needs arising from the intertwined influences of human activities and natural factors. In this context, digital twin technology, positioned at the forefront of information science and technology, offers an innovative solution to address the challenges posed by rural ecological landscapes. Digital twin services need to span the whole process of rural ecological landscape management and control as much as possible. This includes information collection and integration, ecological environment cognition, generation and testing of management and control schemes, implementation of management and control schemes, feedback on management and control processes, and adjustment of management and control schemes. In this process, the advantages of digital twins manifest in information transfer, interaction, and control behavior guidance. They include dynamic mapping feedback, high-precision simulation modeling, efficient data acquisition and management transmission, and intelligent simulation analysis [24, 55], as corroborated by the outcomes of existing digital twin applications in urban and rural control [1, 40, 43]. Traditionally, the comprehension and administration of rural ecological landscapes were human dependent, relying on manpower and past experience. Digitization merely involved the transformation of paper-based information into electronic data. In contrast, digital twins offer a more realistic data fusion model, a swift data analysis process, and simplified access to business execution and functions. They maximize the value derived from virtual rural ecological landscapes. This approach supports multiple functions, such as analysis, identification, evaluation, planning, design, and control, to promote the scientific, sustainable and intensive utilization of rural ecological landscape resources. Specifically, the digital twin service scenarios span four categories: status monitoring and analysis, strategic plan generation, management and control behavior implementation, and participant interaction.

First, the monitoring and analysis of the current situation are performed to achieve an in-depth understanding of the temporal and spatial changes in the rural ecological landscape. Through the Space–Air–Ground Integrated

Data Collection System and multiparty network data resources, data on the rural ecological landscape environment, including vegetation status, soil quality, and water body conditions, can be accurately obtained. The acquisition of these data provides a basis for further scientific research and the formulation of corresponding management strategies.

Second, the generation of strategic solutions is based on the extension of the current monitoring data. Scientific and reasonable protection and development strategies should be formulated under the principle of sustainable development. Land use planning, the most critical aspect of rural ecological landscapes, combines monitoring data for the rural ecological environment and land planning principles. This approach aims to balance the relationship between human activities and ecological protection, avoid overdevelopment and environmental damage, and achieve an ecological balance and sustainable development. According to the guidelines for evaluating the carrying capacity of resources and the environment and the suitability of land space development issued by the Ministry of Natural Resources of China, land space can be divided into extremely important areas for ecological protection, important areas for ecological protection, suitable areas for agricultural production, unsuitable areas for agricultural production, and unsuitable areas for urban construction [15]. The zoning results will be utilized to formulate China's national spatial control program, known as the "Three Zones and Three Lines" program. The "Three Zones" encompass three categories of national land space: urban space, agricultural space, and ecological space. Correspondingly, the "Three Lines" represent the three control lines for urban development boundaries, permanent basic farmland, and the red line of ecological protection, these lines are delineated within the urban space, agricultural space, and ecological space, respectively [51, 53].

The next step is to perform further protection, development, and construction behavior planning and propose corresponding development measures for different land use zones. For example, strict protection measures should be formulated to restrict human activities and control development and construction. Rational agricultural development plans should be formulated, and the planting areas of different crops should be rationally divided to ensure the diversity and sustainability of agricultural production. The total amount of construction land and development intensity should be controlled to avoid excessive expansion and negative impacts on the environment.

Third, the implementation phase of control involves implementing the developed strategy plan in practice. On one hand, the bottom line of development is strictly controlled. Based on real-time information feedback from digital twins, land transformation is closely monitored to ensure that the actual use of land in the "Three Zones and Three Lines" scheme aligns with the plan. On the other hand, the implementation of a series of environmental protection measures can be optimized. Digital twins, combined with artificial intelligence methods involving agricultural automation, robotics, and drones, can promote the optimization of ecological protection, agricultural production, and societal comfort [31].

Finally, participant interaction is key to ensuring the realization of functional needs in rural ecological areas. The participating subjects in rural ecological landscape control encompass the government, villagers, and experts. The collaboration and interaction among these entities contribute to achieving a balance of interests among multiple parties, thereby providing more comprehensive and scientific support for the planning and management of rural ecological landscapes. Digital twin technology is used to simplify the implementation of related tasks and improve the efficiency of relevant technicians and managers. Through network construction, cooperation and participation between different subjects are promoted to enhance communication efficiency. In addition, public participation, government–community cooperation, expert decision-making, consultation and other rural ecological landscape governance behaviors are encouraged, and common ecological protection goals should be established.

The composition of the digital twin framework

The most fundamental definition of a digital twin is a virtual representation of a physical system (and its associated environment and processes) that is updated and virtualized through the exchange of information between physical and virtual components [35]. A twin is composed of three main parts: the physical entity in real space, the virtual representation of the entity in virtual space, and the data and information that links the virtual and real entities [13]. On this basis, various scholars have proposed corresponding improvements based on cognitive understanding. Tao et al. constructed a five-dimensional digital twin model through the application of four modules: a physical entity, a virtual entity, twin data and services, and connections between modules [33]. Wang et al. developed a four-dimensional digital twin model for security based on the characteristics of the security field. The digital twin was created based on the corresponding physical entity, virtual entity, runtime, and connections between the physical and virtual entities [37]. The digital twin of the rural ecological landscape includes the most basic physical components of the rural ecological landscape, the twin model of the rural ecological landscape, the service environment of the rural ecological landscape, and the twin data generated based on corresponding interactions. However, in practice, the development of the twin model, the operation of the service environment, and the management and invocation of the twin data are all achieved with a digital platform. With a human–machine integrated system composed of computer hardware, network and communication equipment, computer software, platform users, and rules and regulations as components, mappings of the real rural ecological landscape environment and real-time communication pathways between the virtual and real environments can be obtained (Fig. 1).

The rural ecological landscape twin model aims to accurately reflect the morphological characteristics of the rural environment in virtual space while conveying the information embedded in the human-interpreted ecological landscape system. Therefore, the model comprises a rural three-dimensional (3D) substrate model and an ecological landscape multi-information model. Together, these components encompass the morphology and attributes of the rural ecological landscape in the multidimensional digital space. The rural 3D substrate model serves as a 3D "base" derived from the 3D reality model, the 3D artificial model, a digital elevation model (DEM), and a digital surface model (DSM). The model visually represents the characteristics of the rural ecological landscape and provides a three-dimensional display foundation for the various types of ecological landscape information. Simultaneously, the ecological landscape multi-information model integrates multisource heterogeneous data for the rural ecological landscape. Notably, it aligns and superimposes discrete biomorphic information within the same georeferenced coordinate system. Finally, temporal features are introduced into the three-dimensional spatial model to establish an integrated multitemporal data model to construct twin models for all components of the rural ecological landscape.

Corresponding to the digital twin service scenario, the rural ecological landscape service environment encompasses the analysis, control, and simulation domains. To effectively protect and control rural ecological landscapes, a fundamental understanding of their characteristics is essential. The use of an intelligent information processing and rule reasoning model within the analysis

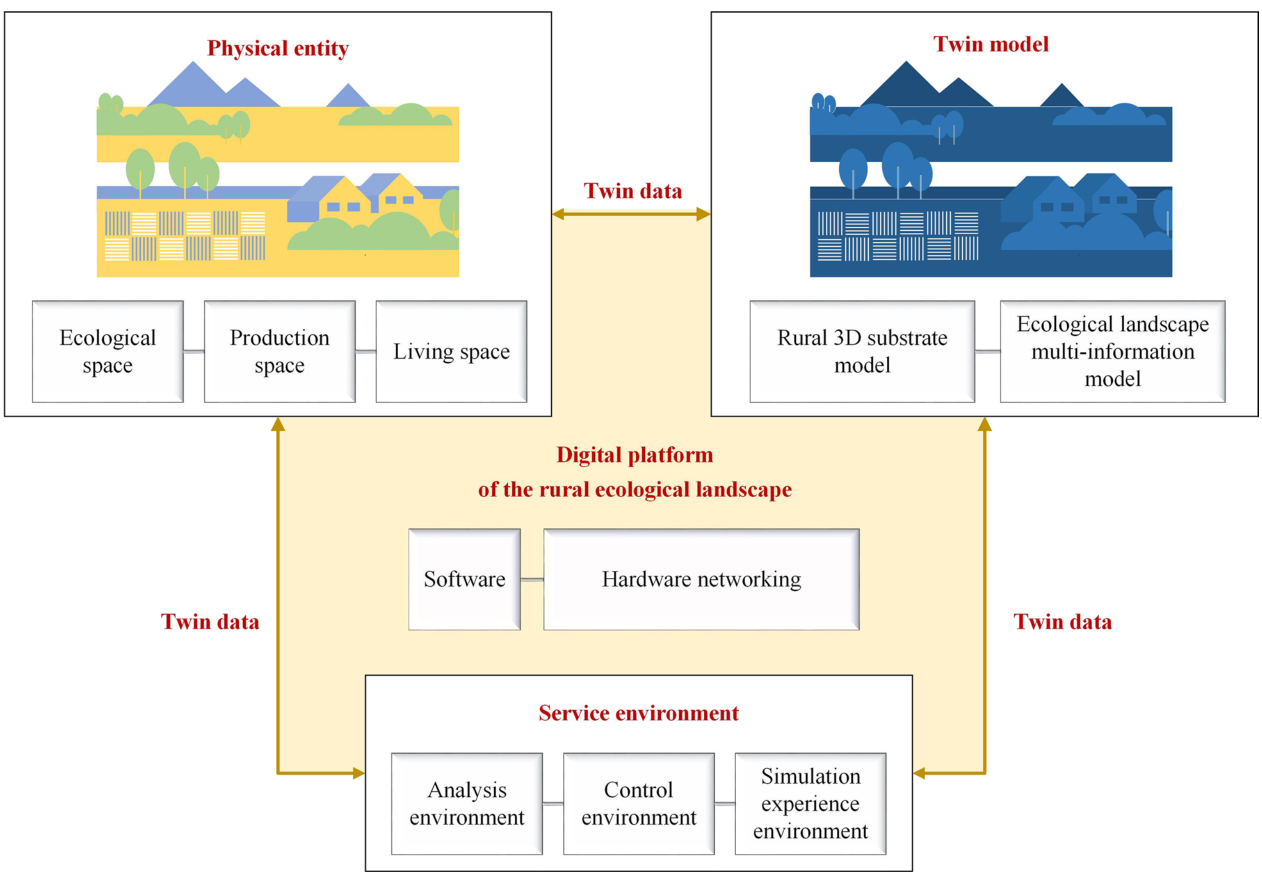

Fig. 1 Composition of the digital twin framework

environment allows experts, scholars, and technicians to efficiently screen, identify, and summarize information from vast and complex data sets. This approach enables precise ecological landscape analysis and evaluation, thus enhancing judgment and decision-making for government departments and guiding the formulation of strategies and plans. The control environment is used to actively monitor land circulation and environmental risks, identify sudden activities and disasters, issue warnings for undesirable behaviors, and ensure the quality and safety of the ecological environment. Moreover, this method facilitates multiparty communication based on real-time monitoring, and internet technology is used to aid government departments in issuing control policies and early warning notifications. Feedback from residents, the integration of suggestions from experts and scholars, and actual control effects are used to guide further research and development. The simulation experience environment, comprising a basic three-dimensional display, a typical scene presentation, and a virtual simulation, provides a visualization of a high-quality virtual rural ecological landscape. This allows the perception of information at different levels through multiple spatial dimensions and viewpoint switching.

The realization and application of the digital twin for rural ecological landscapes hinge on the digital platform as a carrier. Multiple service environments and application interfaces are integrated to foster communication and cooperation among different groups. Fully understanding the environmental characteristics and functional requirements of rural ecological landscapes is crucial for integrating existing digital twin platform construction technology. The platform construction goal is to support the convergence, fusion, and processing of twin data associated with spatial morphology, ecological processes, and control processes. Multiple application scenario service environments should be supported. From a platform construction technology perspective, platforms should exhibit high development efficiency, support flexible access methods and smooth cross-platform docking, and provide high degrees of user friendliness and accessibility.

The content of the digital twin

The ecological–production–living space classification system serves as the foundation for the development and exploration of scientific plans for these spaces. This concept is based on the predominant land use functions, and the structure of land use is pivotal for maximizing functionality. Hence, the classification system should be directly associated with existing land use types, and logical connections and a classification system between land use types and functions should be established [17]. This construction enables the formation of a scientifically sound ecological–production–living space. According to the Classification of Land Use Status (GB/T 21010–2017), the Guidelines for the Classification of Village Planning Land (Jiancun [2014] No. 98), and related research results [8], the classifications are as follows: the ecological space corresponds to woodland, grassland, water area, and other ecological land types (e.g., saline–alkali land, sandy land, bare land, bare rock, and gravel land),the production space corresponds to agricultural production land (cultivated land, garden land, agricultural facility land, etc.) and industrial production land; and the living space corresponds to settled land (e.g., residential land, commercial land, and land for public administration and public services), transportation land, and other types of human-centric land (special land and idle land).

Ecological–production–living spaces are not isolated environmental areas, and their ecological impacts and interactions must be considered within broader rural ecosystems. The synergistic effects of the atmospheric environment, geographical environment, and biological activities should be integrated to recognize and adjust land functions through multiple factors. From the standpoint of the landscape ecosystem, the rural ecological landscape encompasses biological communities, ecological factors, and environmental conditions [54], with related elements such as climate, vegetation, soil, topography, hydrology, and human-centric factors, such as land use [39]. Consequently, the twin elements of rural ecological landscapes can be categorized into land-use situations, habitat conditions, biological communities, and construction projects. The structure of twin ecological–production–living spaces includes the environmental conditions, the activities of humans, animals, and plants; and the transformative behavior of humans in the context of the rural ecological environment.

In the construction of subsequent digital twin models, it is necessary to determine the specific twin content, which is usually based on the properties of a physical entity, to express the corresponding geometry, physics, behaviors, and rules. The goal is to map the geometric morphology, physical properties, and behaviors in response to internal and external mechanisms, tacit knowledge generated by historical data, and other information [32]. Most of the twin elements of rural ecological landscapes are natural rather than artificial factors, so their inherent structure and associated information are complex. More attention has been devoted to the interactions and regulatory mechanisms among elements in management and control work than to other factors. Some physical and behavioral information does not need to be considered in detail. Therefore, to enhance the intelligent management and control of rural ecological landscapes, information mapping and twinning should be carried out from two perspectives: spatial morphology and ecological processes (Fig. 2).

Twins in spatial morphological research can be used to restore the geometric morphology, color, material, and spatial location properties of rural ecological landscape elements. On one hand, this involves individual twin elements, and on the other hand, the relationships among twin elements are considered. First, three-dimensional modeling technology can be used to construct a model of the rural ecological landscape. This approach not only restores the shape of landscape elements but also enables interaction with and exploration of the virtual environment, facilitating the realization of geometric twinning and helping users better understand the composition of rural ecological landscape elements. Second, digital twin technology can be used to simulate the color and material of rural ecological landscape elements, enhancing the realism of virtual scenes. A color or material twin can not only reflect the visual characteristics of the landscape but also provide a realistic experience for the observer. This approach allows the exploration of the influence of different combinations of colors and materials on the perception of the landscape. Finally, digital twin theory is employed to restore the spatial distributions of different elements, aiding in understanding the correlations and interactions among elements. This approach facilitates studies of the impact of different element layouts on ecological processes and visual effects through spatial location twinning.

The ecological processes of rural ecological landscapes involve interactions and changes among various biological and environmental elements in nature. These processes collectively impact biodiversity, the ecological balance, and the relationship between humans and nature. Therefore, the ecological process twin of rural ecological landscapes includes three sets of factors: biological ecological characteristics, abiotic environmental characteristics, and ecological evolution processes. The aim is to represent implicit internal laws through the synthesis of twin information, providing a scientific basis for management and control. First, the use of digital twin technology for simulating biological and ecological characteristics can aid in modeling the distribution of and changes in different biological elements in rural landscapes [34]. Based on ecological models, dynamic changes in biological communities can be simulated, and the impact of human activities on biodiversity and ecological balance can be explored [41]. Second, the simulation of abiotic environmental characteristics covers climate, soil, water, and other factors. Information on environmental conditions can be obtained through digital twin technology to reveal the influences of abiotic environments on ecological processes. Finally, based on the data collected

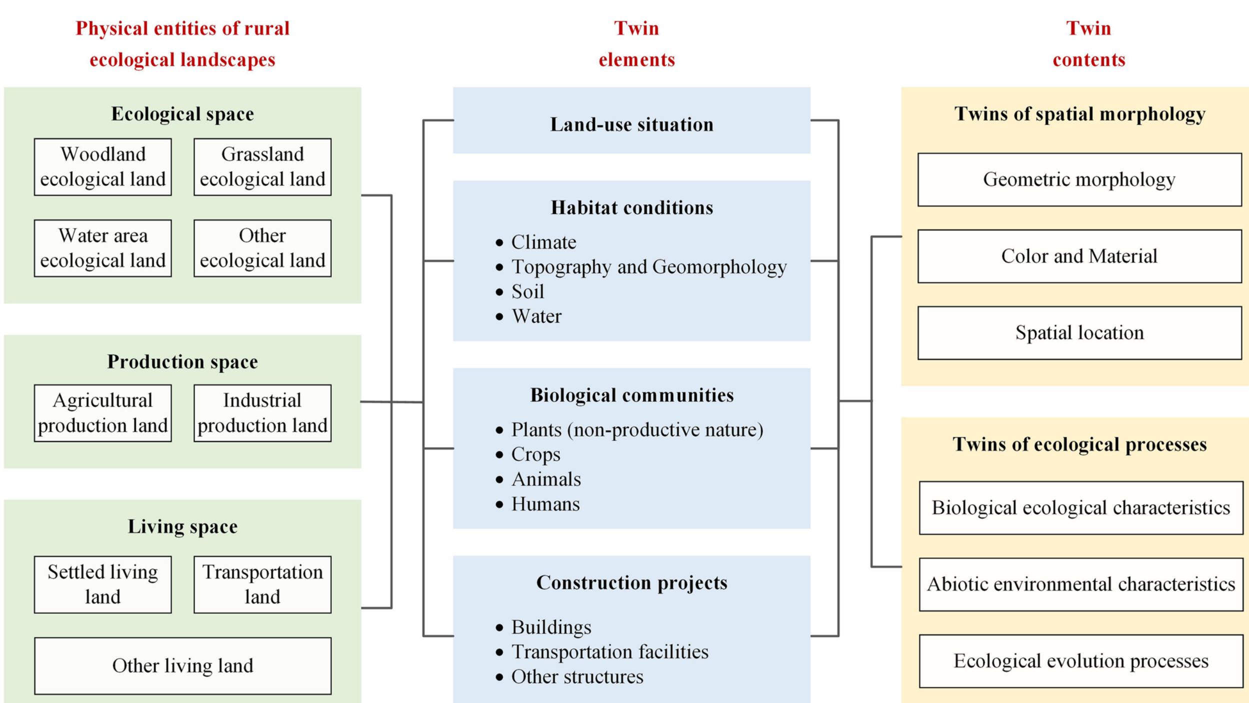

Fig. 2 Physical entities of the rural ecological landscape and corresponding twin content

and the twin relations at different timepoints, the characteristic changes in ecological landscape organisms, environmental elements, and landscape patterns can be recorded. This approach provides the possibility for simulating changes in rural ecological landscapes based on the influence of different disturbances and natural factors, thus facilitating the further analysis and prediction of evolutionary trends.

Proposed method

In contrast to the swift changes in physical entities in the industrial context, the rural ecological landscape environment generally undergoes comparatively gradual changes. Therefore, the pivotal focus lies in enhancing the comprehensiveness and circulation of information in rural ecological landscape management and control. Rather than excessive reliance on sensors and sensing data, as emphasized in traditional digital twin approaches, the proposed method shifts attention toward effectively simulating the complexities of the rural ecological landscape. The emphasis is on leveraging digital twin technology to facilitate and enhance management and control processes.

Mapping and fusion of systematic information

The first step is to select the mapping method, enabling the acquisition of data that can effectively reflect the relevant system information (Fig. 3). When considering rural areas as the research focus, a comprehensive understanding is required, necessitating both rapid overall cognition and a more detailed examination of key areas. The data precision and richness required for each area in the mapping model differ, emphasizing the need for a non-"uniform" model. Therefore, a combination of macro-mapping and micro-mapping is essential. In this context, macro and micro are relative to the individual villages to be twinned, focusing on different levels of the twinning model—corresponding to the whole and the details, respectively. This approach aims to deliver a more detailed and efficient integrated twinning solution. Macro-mapping provides data information for studying the countryside as a whole, offering fundamental knowledge of the overall ecological landscape. Conversely, micro-mapping concentrates on accurate microlevel cartographic information for specific geospatial entities, such as rural buildings, bridges, and facilities requiring focused protection or ecological protection areas necessitating mapping with multiple types of ecological indicators to meet various spatial needs.

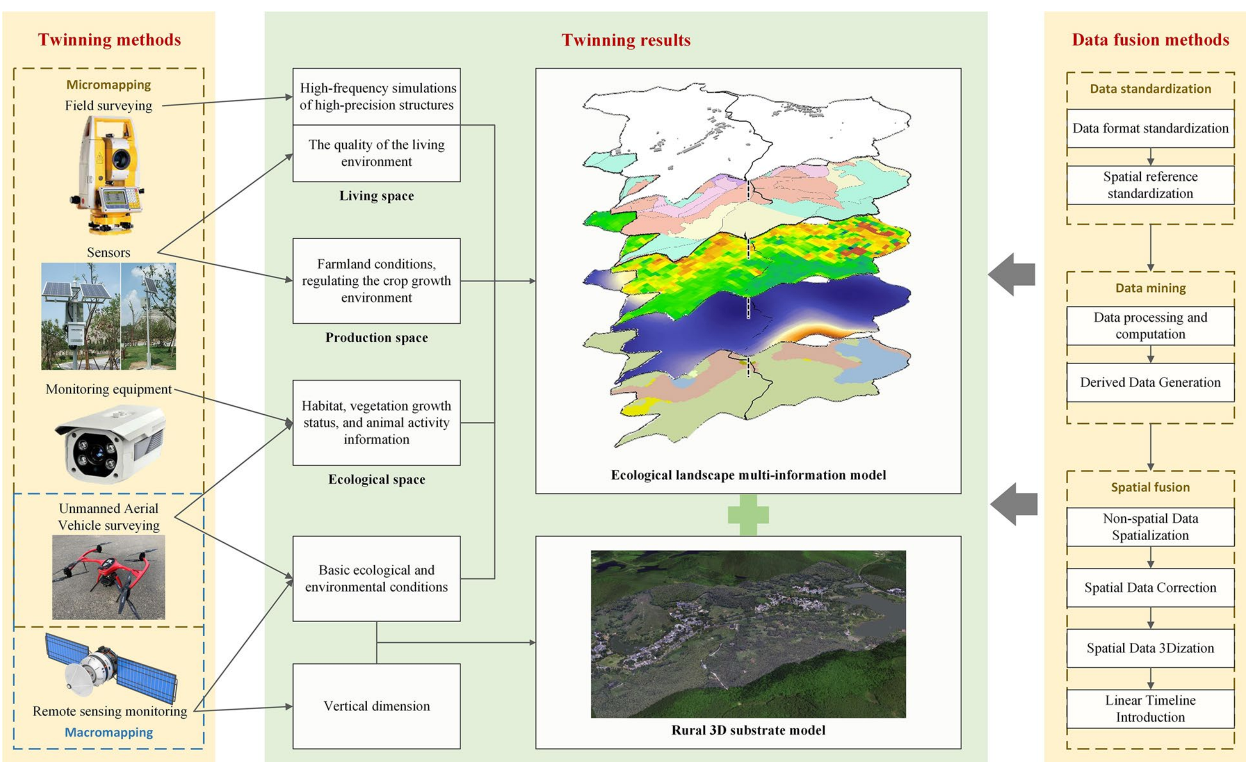

Fig. 3 Selection of information mapping methods and convergence paths

This approach aims to provide a more detailed and efficient comprehensive twin scheme. First, considering the rapid data acquisition, stable update speed, and wide information coverage area provided by satellite remote sensing and unmanned aerial vehicle (UAV) surveying, remote sensing monitoring and UAV aerial surveys were utilized to swiftly map the rural ecological landscape at the macrolevel. The obtained data included information on ecological and environmental conditions such as land surface type, vegetation conditions, hydrological processes, and human activities. In addition, spatial conditions in the vertical dimension, such as elevation, slope, aspect, surface height, canopy height, and building height, in ecological–production–living spaces must be understood to accurately model environmental conditions and spatial relations. Second, to address the specific management and control needs of ecological–production–living spaces, detailed mapping of twins was performed. To minimize artificial interference in the ecological space, UAV aerial surveys and monitoring equipment were used to obtain abundant habitat, vegetation growth status, and animal activity information at high resolutions. Sensors were utilized in the production space to detect the conditions of farmland, enabling timely interventions and the regulation of the crop growth environment. The virtual living space was designed to reflect the visual characteristics of and human activities in nearby settlements. On one hand, this approach was combined with field surveying and mapping for high-frequency simulations of high-precision structures. On the other hand, the quality of the living environment was evaluated with the support of sensor data.

The multisource heterogeneous data fusion method proposed by Yuan et al. [48] was employed for the fusion of systematic information and involved data standardization processing, data mining, and spatial fusion. The first step was to standardize the original data, ensuring a unified data format and spatial reference coordinate system and establishing the basic conditions for information fusion. The data were divided into spatial data and nonspatial data classes, with the specific data format specifications presented in Table 1. Some spatial data had a nonunified reference system, hindering accurate alignment. To address this issue, the spatial reference coordinate system of all spatial data was standardized to the 2000 National Geodetic Coordinate System. The second step was data mining. To gain a more profound understanding of the rural ecological landscape, it was imperative to process the necessary data based on the analysis objectives and existing analysis models. This process enabled the generation of multivariate data sets with broad coverage. Finally, spatial fusion was necessary to achieve the positioning, fusion, and visualization of data within a multidimensional virtual Earth environment. In accordance with the requirements of data visualization, a portion of the nonspatial data was utilized as attribute data and linked to the corresponding geographic data, thus forming spatial vector data. GNSS technology was further employed for spatial correction and registration based on key calibration points. A rural 3D substrate model served as the basis of 3D attribute acquisition, aiding in the positioning, integration, and presentation of the multiple types of ecological landscape information. This approach ensured the 3D visualization of information with the rural ecological landscape mapping model and supported the 3D mapping and linking of multidimensional data in a unified spatial reference system. Finally, to reflect the evolutionary process of the rural ecological landscape and illustrate the coevolution characteristics of twin data interactions, the introduction of the temporal dimension was essential. Dynamically updated attribute tables were displayed in the form of dynamic charts (e.g., sensor data), and dynamically updated spatial data were compared with data over time based on a rolling function.

Table 1 Data format conversion standards

Data types		Existing formats	Standard formats
Spatial data	Oblique photography model data	OSGB, OBJ, 3D Tiles	3D Tiles
	Vector data	Shapefile, DWG	Shapefile
	Raster data	DAT, TIFF, IMG	TIFF
Nonspatial data	Video files	AVI, MP4, FLV	MP4
	Audio files	MP3, WAV, M4A	MP3
	Digital images	JPG, JPEG, BMP, PNG, GIF	JPG
	Text files	DOC, TXT, PDF	TXT, PDF
	Form files	XLS, XLSX	XLS, XLSX

Database construction and management

To facilitate the management and utilization of data, the data files were treated as the fundamental management units. First, starting from top-level management and considering the attributes and characteristics of the data, it was essential to differentiate and classify the data to form a data set. In the context of rural ecological landscape research, the rural ecological landscape data were categorized into four types: basic rural ecological landscape data, rural ecological landscape analysis and evaluation data, rural ecological landscape control and governance data, and rural ecological landscape 3D simulation data. The specific subdata sets used are detailed in Fig. 4. On the other hand, based on the underlying physical structure of the data, the files were systematically refined into data elements and data items layer by layer, facilitating the recording of specific rural ecological landscape information.

Building on the foundation of database entity construction, it is essential to utilize the database management platform for data processing, storage, removal, and invocation. Initially, data extraction, conversion, and calculation were conducted in accordance with the relevant data storage standards and processing rules. Standardized data were generated with the support of data encoding, attribute transformation, and content integration mechanisms. The data coding rules were obtained from "GB/T 2260 Administrative Division Codes of the People's Republic of China" and "GB/T 10114 Rules for Compiling Administrative Division Codes below County Levels."

With Oracle as the primary database management platform, the main database was established. In addition to nonspatial data, a spatial geodatabase was integrated into the database with ArcGIS SDE. Following the organizational structure of the rural ecological landscape database, the data were classified, partitioned, merged, stored, and processed to complete the data organization operations. Eventually, an application programming interface (API) was established to accept user instructions. The IP address of the interface is provided in the access data configuration table, enabling the invocation of demand data with the rural ecological landscape twin platform to support various applications.

The construction of the digital platform

In this paper, we propose a hybrid C/S and B/S architecture with distributed systems as the primary service core. The overall architecture of the platform is based on a hierarchical model supported by HTML technology, desktop application development technology,

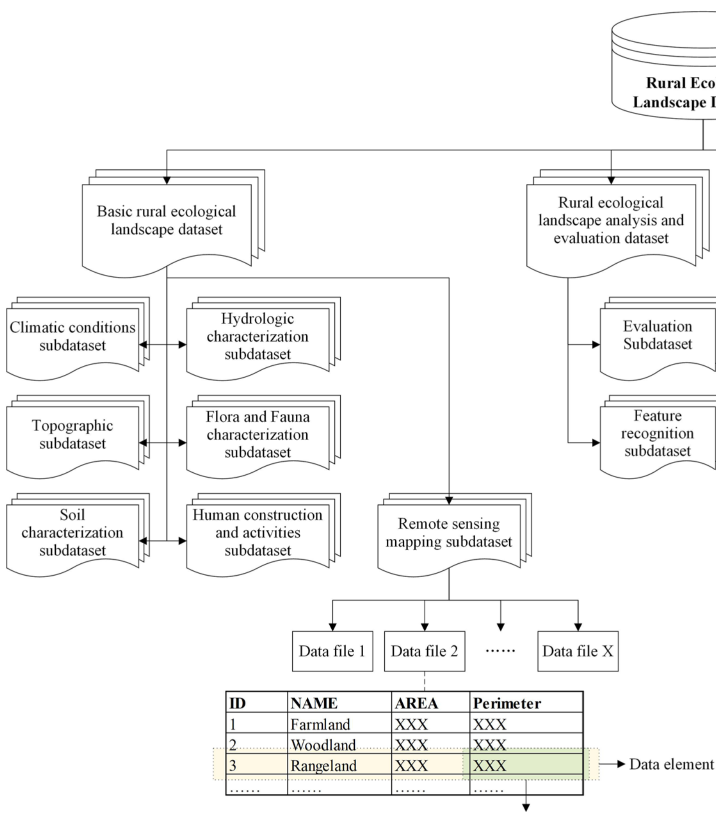

Fig. 4 Organizational structure of the database

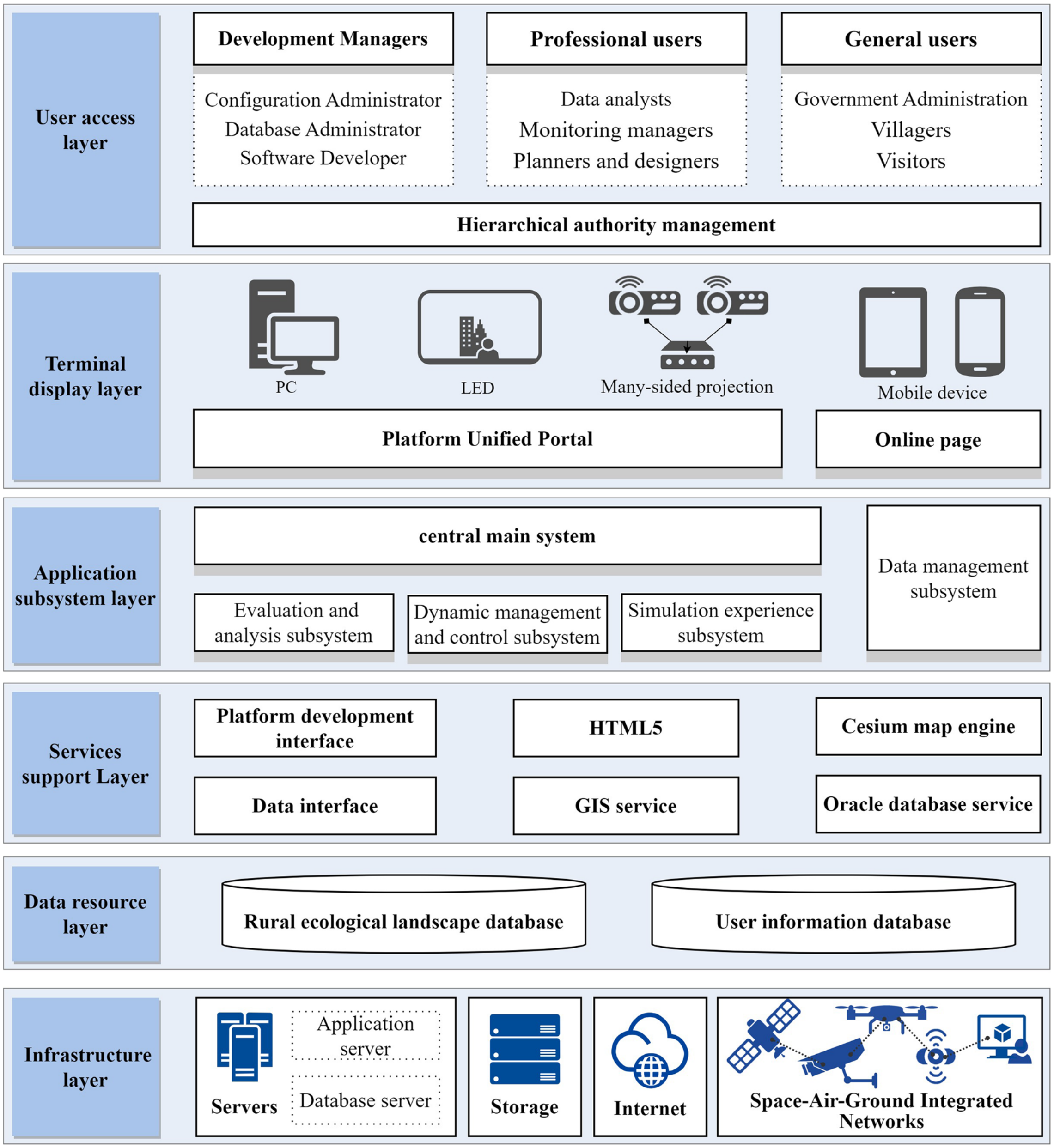

Fig. 5 Overall architecture of the digital twin platform

geographic information system development technology, 3D space modeling technology, and data analysis and visualization technology, among others (see Fig. 5). Furthermore, the digital twin platform is generated with a certain functional architecture. The platform architecture is specifically developed considering the organization and design of the platform interface, platform programming, the loading and updating of data and subplatforms, and the verification of platform operations.

First, we design five application function modules: the data integration management subsystem, basic operating subsystem (i.e., central main system), analysis and evaluation subsystem, dynamic management and control subsystem, and interactive simulation and experience subsystem. The data integration management subsystem is divided into three modules: data fusion, data management, and data loading. Through the data processing function, this subsystem transforms the original data into standard data that can be fused and applied, builds a rural ecological landscape database, and effectively integrates and manages all kinds of data to support the implementation of digital control.

The analysis and evaluation subsystem includes an analysis and mapping module and a feature extraction and evaluation tool module. The analysis and mapping module includes two functional groups—graphic drawing and map making—to provide a means of visualizing and analyzing the rural ecological landscape. The feature extraction and evaluation tool module includes three functional groups—the feature extraction tool, thematic analysis and evaluation tool, and general spatial analysis tool—to provide multilevel ecological landscape analysis and evaluation tools.

The dynamic control subsystem aims to realize real-time monitoring and regulation of land use and the ecological environment through four modules: land use monitoring, ecological environment quality monitoring, control information disclosure and public feedback. The land use monitoring module is committed to providing in-depth insight into dynamic changes in rural land use. The ecological environment quality monitoring module realizes real-time monitoring and assessment of rural ecological environment quality through advanced sensing technology. The public feedback module promotes public participation in ecological control, and it establishes a mechanism for multiparty participation and feedback.

The interactive simulation experience subsystem includes the view interactive operation module and simulation effect adjustment module, which focuses on providing an immersive and vividly realistic virtual simulation experience. The view interactive operation module provides rich map browsing and management functions, and the simulation effect adjustment module enhances the user's perception of the rural ecological landscape through realistic weather and lighting effect adjustment functions to create a real rural experience.

In the application subsystem layer, the platform functions and integrated modules are organized in a distributed architecture, with different components of the digital platform distributed across multiple nodes. This facilitates communication throughout the network, supporting decentralized data storage and processing for enhanced performance, scalability, and flexibility. The unified portal serves as the central system, integrating the rural ecological landscape evaluation and analysis subsystem, the rural ecological landscape dynamic management and control subsystem, and the rural ecological landscape simulation experience subsystem. These subsystems are fused through loosely coupled service components. In addition, a data management subsystem is established on the database server, and it connects to the main system through the data interface for platform data management and application.

In the service support layer, the technical services and corresponding architecture are provided, encompassing the platform development interface, data interface, HTML5, GIS service, Cesium map engine, and Oracle database service. Each service plays a unique role in collaboratively supporting the platform's business needs. The platform development interface provides a standard interface for the distributed subsystems, promoting function expansion and optimization. The data interface ensures information flow among different components, supports normal subsystem operation and enhances overall synergy. HTML5 serves as the cornerstone for the cross-platform user interface, ensuring a consistent user experience. GIS services and the Cesium map engine provide geographic information visualization and interaction capabilities. The Oracle Database Service supports underlying data management, ensuring secure storage and efficient retrieval through a high-performance, reliable database system.

The infrastructure layer is crucial for the smooth operation of the software platform, and servers and storage, networking, and data acquisition systems work collaboratively. Servers handle computing and application execution, the storage system provides reliable and persistent storage, and the network facilitates rapid data transfer. The data acquisition system collects real-time multisource data, providing rich multidimensional information support. Users interact with the platform through the network, and the server processes requests and retrieves and stores data. The data acquisition system continuously updates the data in real time. This collaborative system ensures quick responses to user requests, provides a robust foundation for upper-layer business logic and application services, delivers real-time updated data, and supports various types of operations.

Applications and discussion

Experimental data

Since villages in different regions may exhibit diverse ecological landscape characteristics, the proposed approach is intended for nationwide application and beyond. Therefore, six villages in North China (including Huangshandian Village in the Fangshan District, Beijing, and Badarenggui Gacha in the Xing'an League, Inner Mongolia Autonomous Region), East China (including Huanglongxian Village in Nanjing, Jiangsu Province, and Changkou Village in Sanming city, Fujian Province), Northwest China (Siyuan Village in Aksu city, Xinjiang Uygur Autonomous Region), and Southwest China (Liyuan Village in Chengdu city, Sichuan Province) are selected. The rural ecological landscape twinning data of these villages are collected, and data from multiple heterogeneous sources are overlaid to generate simulated integrated multitemporal 3D village models in a global environment. Subsequently, independent information query and control service systems are developed for each village, and they are integrated into a digital twin platform. The platform provides a unified access portal to access the independent interfaces of all villages. System functionality and performance tests are then conducted to verify the feasibility of the digital twin framework.

Experimental environment

(1) Development environment

Hardware:

- Processor: Intel (R) Cores (TM) operating at 2.0 GHz with 4 cores or above
- Memory: 16 GB or more RAM
- Hard disk: 512 GB or larger hard disks
- Display: a display device with a resolution of 1024 × 768 or greater

Software:

- Operating system: Windows 7 and above
- Development platform: Microsoft Visual Studio 2012
- Development language: C#
- GIS platform: ArcGIS Engine 10.2

(2) Operating environment

- Operating system: Windows XP and Windows 7 or above
- Interface browsers: IE 8.0, Chrome, and Firefox
- Service permissions: the ArcGIS 10.2 License Service
- Database server software: Windows 2008 or later and Oracle 11 g or later

(3) Platform security

The security assurance of the digital twin platform is approached from both the managerial and technological perspectives, aiming to minimize potential threats, enhance system security, and ensure the appropriate protection of sensitive information. Standardizing internal security standards and processes, along with establishing access control and identity verification mechanisms, contributes to the establishment of a comprehensive and well-organized security management framework. Security is achieved by implementing firewalls, intrusion detection systems, encryption technologies, vulnerability management, patch updating, anti-virus and malware protection, and security auditing and monitoring. These measures collectively ensure a robust security infrastructure for the digital twin platform.

Platform generation and application

Users access the digital twin platform through a unified portal entrance, and users with different identities participate in various digital control stages, aligning with distinct business needs and processes. User identities encompass development managers, professional users, and general users, with all of these users having unrestricted access to the central system, simulation experience subsystem, and dynamic management and control subsystem. Professional users, government administrators, villagers, and visitors engage with the dynamic management and control subsystem to offer feedback and adjustments. Development managers oversee and maintain the platform's operations and access the data management subsystem to modify the format and content of the data, shaping the database of the platform. Professional users, including data analysts, monitoring managers, and planners and designers, access the evaluation and analysis subsystem to generate control partitioning schemes.

Tailored platform interfaces and terminals are developed based on different user scenarios, ensuring the achievement of rural ecological landscape control business in each real environment through effective human–computer collaboration (see Fig. 6).

(1) Information querying and 3D visualization

The village domain served as the primary entity for information integration. An independent access interface was constructed for each village. By utilizing the location search function, users can locate and access the target village. Upon connection to the village's proprietary database, the platform displays the ecological landscape data for the village in a centralized manner (see Fig. 7). As data are continually updated and expanded, the platform is able to process data through rapid querying and return multisource rural ecological landscape data using keyword retrieval (see Fig. 8) and classification browsing. In addition, users can click on architectural models or images to obtain the respective attribute information (see Fig. 9).

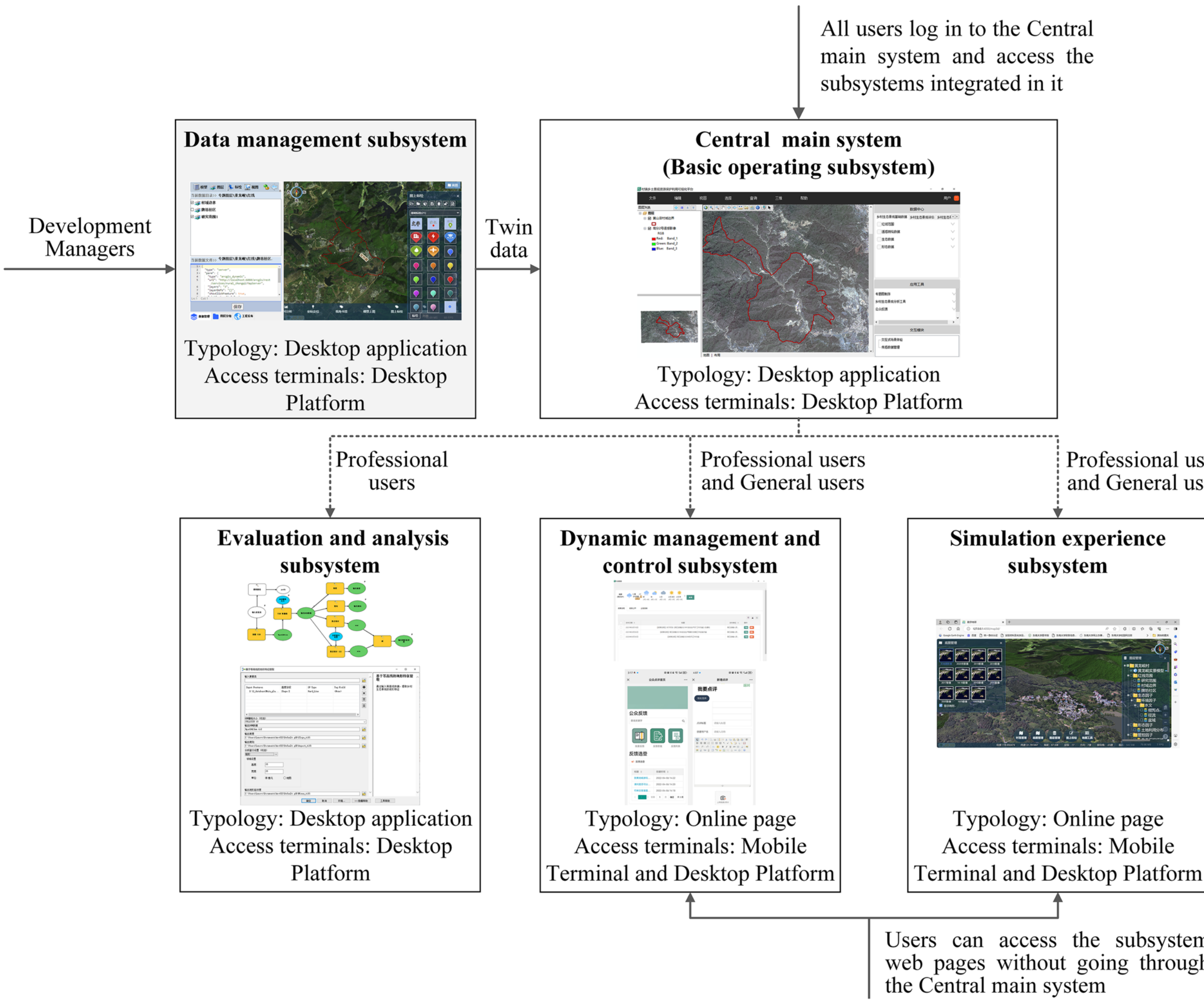

Fig. 6 User access interface and port organization for digital twin platforms

(2) Environmental assessment and analysis

Chen and Wang and their colleagues [4] proposed an evaluation method to depict the current state of rural ecological landscapes. Their research, grounded in the characteristics of rural ecological landscapes in the new period of China, forms the basis for refined management and control of these landscapes [5, 38]. Utilizing this evaluation method, six distinct types of rural landscape management and control zones were identified: development and construction control zones, core agricultural production zones, characteristic livable recreation zones, ecological restoration and management zones, ecological conservation protection zones, and ecological buffer coordination zones (see Fig. 10). The platform allows users to view the boundaries of these zones at any time, enabling comparisons with current land use conditions. This feature facilitates the precise management and implementation of effective strategies. Moreover, 3D analysis functions such as spatial analysis, sunlight analysis, and viewshed analysis are supported (see Fig. 11), and the user's multisensory experience is deepened through real-time analysis in virtual space.

(3) Space control and governance

The implementation of rural ecological landscape management and control requires a dedicated and multichannel monitoring approach. This involves closely monitoring the risks associated with land

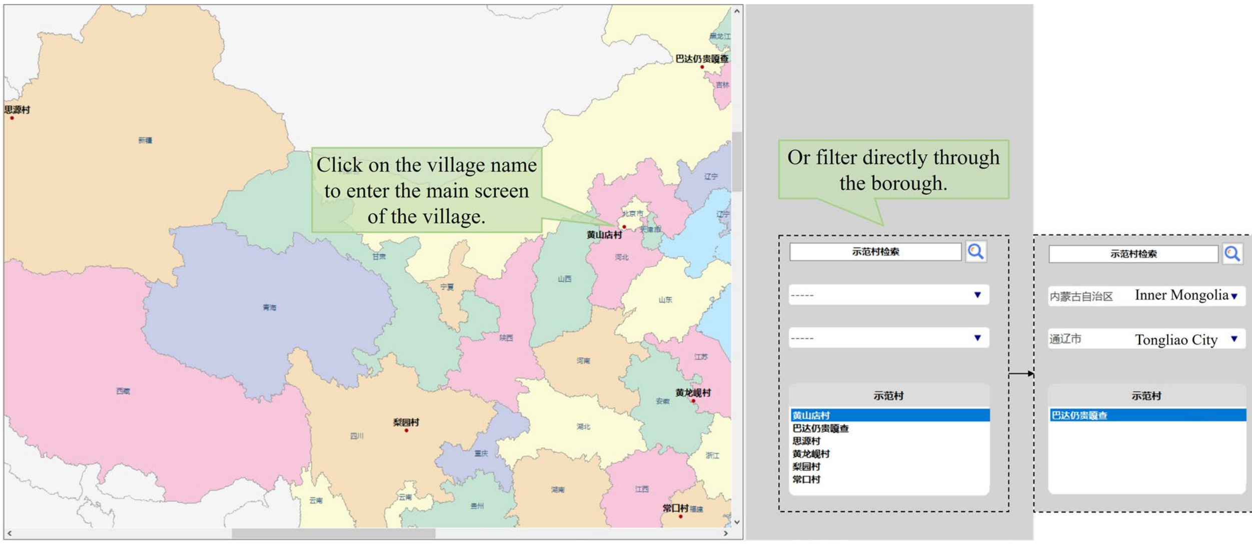

Fig. 7 Selection of the target village

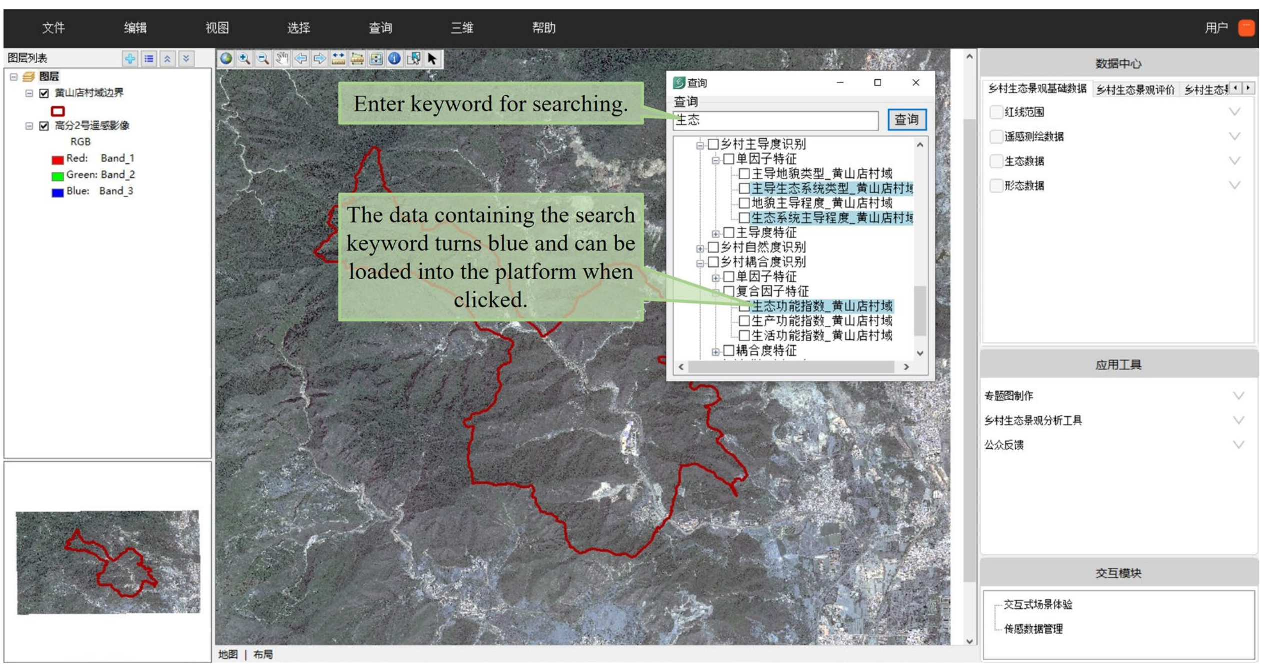

Fig. 8 Keyword-based data querying and loading

and space resources, as well as the ecological environment, through the Internet of Things (IoT). The IoT facilitates real-time monitoring, enabling administrative departments to quickly acquire key control information, make efficient and accurate decisions, and ensure effective implementation. In addition, a communication channel is established among government departments, staff, experts,

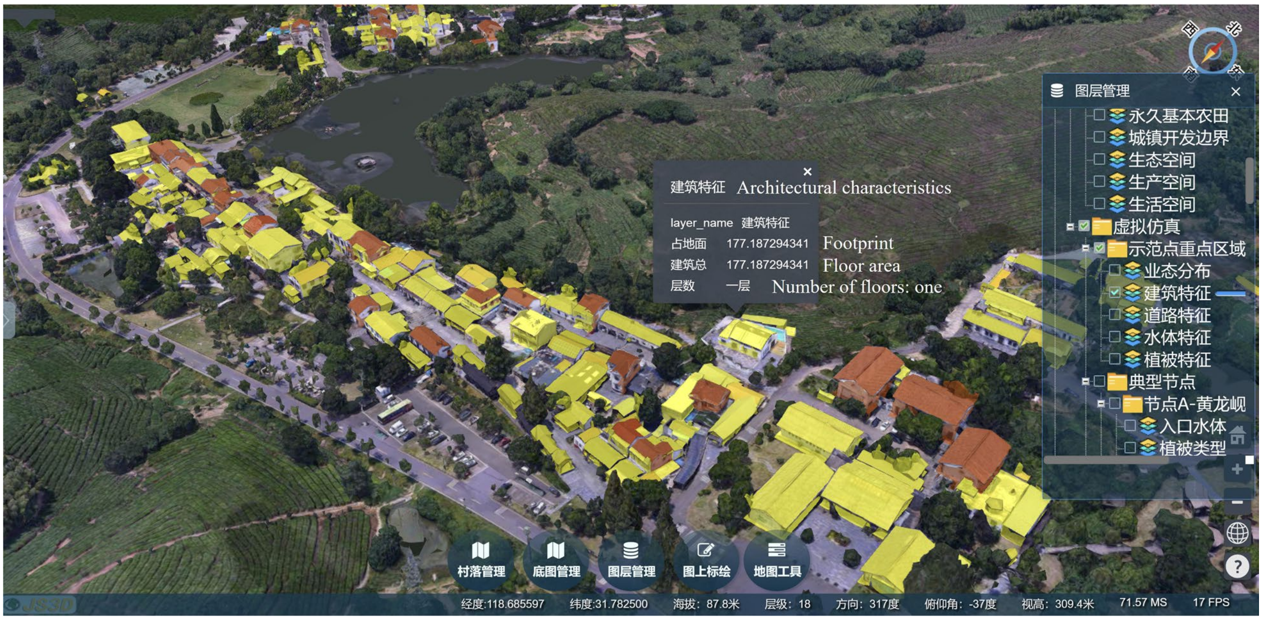

Fig. 9 Graphical representation and information querying realized in a 3D GIS, where different color blocks represent clickable single buildings

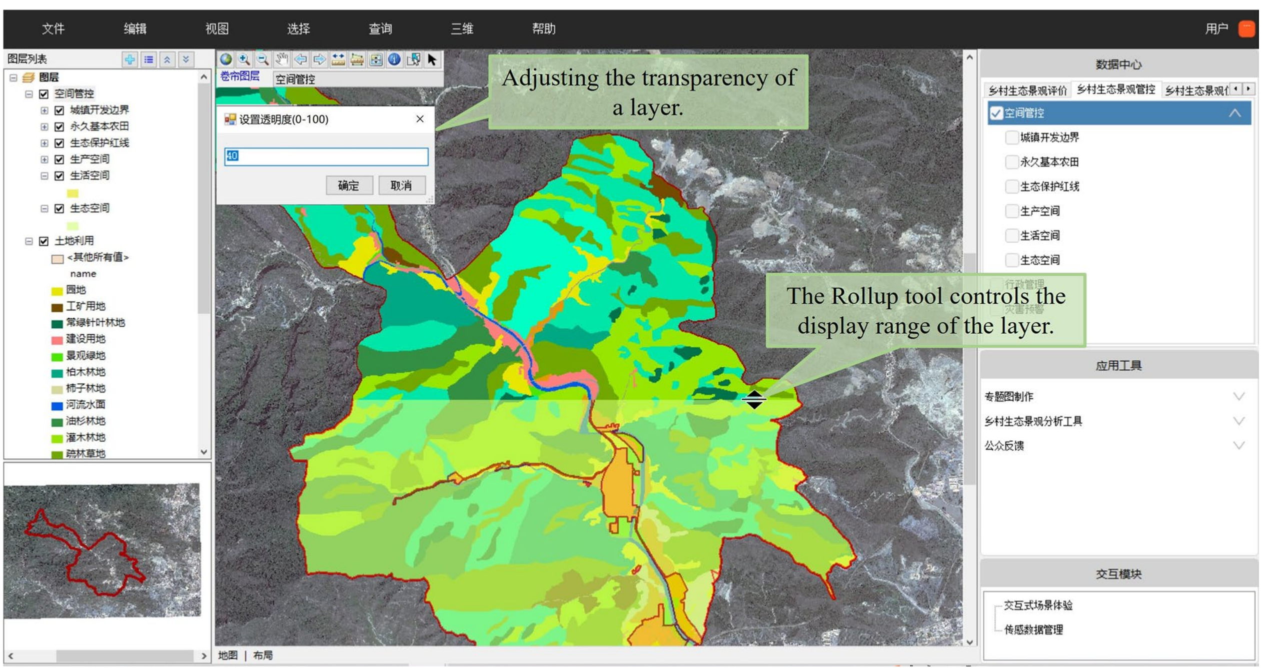

Fig. 10 Transparency modification, use of the rolling shutter tool to overlay environmental assessment results with orthophoto maps and land use distribution maps, and performance of a comprehensive analysis within the given control boundaries

scholars, and villagers (see Fig. 12). This ensures that the platform is well suited for real management and control scenarios, facilitating the digital transformation of "decision-making, supervision, implementation, and feedback–improvement–response." Overall, this approach enhances the governance efficiency of the rural ecological landscape.

Fig. 11 Analysis based on the oblique image mode

Fig. 12 Published results and feedback obtained via public comments through mobile phones. Note: The numbers in the figure represent the correspondence between each button and its pop-up interface

Value and limitations

Discussion of the value of the platform

(1) Strong information processing ability

The key value of the digital twin is not only the digital mapping of specific spatiotemporal information but also the real-time acquisition of information about the whole life cycle of physical objects, enabling the underlying processes to be understood and controlled [18]. Although the rural ecological landscape does not have a clear life cycle, as the center of human activities, it is shaped and frequently disturbed by humans. We observe that land use patterns [19], crop planting structures [20], artificial structural materials, and construction methods [25] in rural areas are undergoing significant changes. This evolving landscape will have immediate or potential impacts on the rural ecological environment, necessitating careful attention and documentation.

With the help of digital devices and methods, we can observe when changes are occurring, but we cannot accurately grasp the speed and extent of these changes, let alone generate theories and knowledge from historical data. The dynamic twin of the rural ecological landscape can encompass rapid and significant changes in the rural environment, help individuals identify major problems in real time, and support the implementation of corresponding countermeasures. This approach establishes positive interactive feedback between ecological landscape changes and human control measures and is conducive to addressing various rural service scenarios.

(2) Overcoming traditional temporal and spatial limitations

The scale of ecological processes perceived by humans through sight, smell, and hearing is termed the "perceptible realm" [12]. Traditional agricultural philosophy aims to achieve the harmony of "heaven, earth, man, and things" by observing changes in the sky, climate, and phenology and organizing agricultural activities accordingly [28]. While this approach has practical significance, its limitations are evident, as noted in studies of rural ecological landscape issues. Notably, this method fails to comprehensively grasp large-scale rural landscape patterns in a timely manner, and scientifically accurate and detailed research based on this approach is often limited at small scales. Rural ecological landscape research requires transcending physical distance constraints to adopt a more macroscopic view of rural areas. The digital twin environment, which acts as "God's perspective," involves a "digital Earth" in virtual space, breaking the temporal and spatial limitations of human perception in the physical world.

Humans and technology generally treat time as a unidirectional one-dimensional factor from the past to the present and the future. While time travel and altering the Earth's laws of motion are currently unattainable, information can be recorded and saved using text, numbers, and images, allowing the past to be understood and the future to be predicted. The virtual space, which relies on the digital Earth, records information about rural ecological landscapes in different periods, and an informational model of multiple parallel states can be constructed. This enables states to be organized into adjustable time sequences, facilitating the retrospective analysis of any time node and providing the possibility to observe the evolutionary process at a given geographic location over time.

Spatially, the digital twin environment enables instantaneous movement and data acquisition, allowing individuals to switch rapidly between geographic locations and access the environment, scenery, and information in remote areas. This capability enhances the understanding and display of rural ecological landscapes. Internet technology further facilitates interactions in the virtual rural ecological landscape, providing a platform for government officials, experts, and villagers to participate jointly in discussions, presentations, and decision-making. Experts can convey scientific knowledge through virtual simulations, while the government and villagers can share their views and experiences. This multiparty participatory approach overcomes the typical limitations of time and space, promoting the intersection of different viewpoints and knowledge. This study provides a diverse and comprehensive perspective regarding the control of rural ecological landscapes and a reference for making control decisions.

(3) The presentation and integration of virtual scenes

The rapid development of virtual technology has led to new possibilities for constructing and presenting rural ecological landscapes. Twin rural ecological landscapes are derived from real rural landscapes, aiming to faithfully restore the phenomena that exist in the real world and the processes behind them. Through advanced modeling and rendering technology, elements such as terrain, vegetation, and water can be accurately reconstructed, resulting in a highly realistic rural ecological landscape.

However, the value of digital twins of rural ecological landscapes extends beyond mere replication. Notably, virtual space is used to reconstruct and understand the real world. Guided by actual needs, twin information represents the external morphology and internal attributes of the real rural ecological landscape, and twins are constructed and expressed based on detailed analyses, judgment processes, and understandings in the context of various goals. This approach represents a dual mapping of the real rural ecological landscape and human perception and understanding. The rural ecological landscape can be selectively expressed in a twin environment, efficiently supporting specific functions and needs without replicating all features or acquiring all information.

Moreover, the twin rural ecological landscape allows for the transformation of the rural ecological landscape within the twin environment. This approach enables the integration of imaginary scenes with real scenes to display and simulate the results of rural planning and design. By leveraging virtual reality technology, the interactions between fictional scenes and real scenes in the physical world can be explored. Users can assess the credibility of fictional scenes by comparing the differences between fictional and real scenes. This goes beyond what the real rural ecological landscape can encompass, representing a crucial application direction of twin-based rural ecological landscapes.

By presenting and integrating imaginary scenes of rural ecological landscapes, systematic studies can be conducted without the need for on-site data collection, saving time and reducing costs. This approach provides visualization tools for decision-making tasks such as planning, design, and control. Information processing through simulating various scenarios and conducting virtual experiments enhances realism and reliability, thereby improving information communication and decision support capabilities. Building on this foundation, this study facilitates the simulation and prediction of ecological phenomena, contributing to a better understanding of the characteristics and evolution of rural ecological landscapes.

Limitations and prospects

(1) First, despite the promising opportunities presented by the emerging concept and technology of the digital twin, it is essential to acknowledge its current limitations and drawbacks. The foremost challenge is the maturity of digital twin technology, with most applications still being in early developmental stages, leaving substantial gaps to be addressed [2]. Quantitative technology limitations pose difficulties in data acquisition and processing, hindering the construction of multiscale, high-precision simulation models. The digital twin data acquired lack comprehensive information, resulting in low prediction accuracy for complex systems. In addition, the influx of massive data places greater pressure on processing and management, presenting a key challenge in improving the accuracy and performance of information analysis. The synchronous integration of virtual and physical space in rural ecological landscapes faces hurdles due to the limitation of the update frequency of twin data.

While we have achieved some technological breakthroughs, such as the development of a 3D fusion method for massive data supported by GNSS and WebGIS [48] and a rapid construction and management method for databases and platforms under the internet, this paper primarily focuses on discussing the framework of rural ecological landscape control using digital twins. The intention is to outline the overall research content and path through this framework, demonstrating the feasibility and value of this research through practical applications. A comprehensive discussion of the technologies used in implementing the framework in practice falls beyond the scope of this paper. It is anticipated that researchers interested in this topic will explore a variety of digital technologies and that the proposed framework can be realized more economically, rapidly, and intelligently with additional time, financial support, and advancements in smart technologies.

Second, digital twin technology involves various types of technologies and demands significant economic and human resources. In practice, deploying equipment for data collection incurs labor and time costs for processing extensive data. In addition, professionals are required for the development and management of software on both the front-end and back-end. While this paper leverages the rapid development of informatization in China and mature database and platform development technology to address some development cost challenges, not all ideas have been fully implemented. Future efforts are expected to reduce the development costs and promote more economical practical application methods with robust support from digital technology.

(2) The digital twin framework proposed in this paper is applied in rural China, but its applicability extends to any rural area requiring digital control of ecological landscapes. This applicability includes the twin model content, corresponding mapping methods, as well as the functional architecture and construction path of the digital twin platform. However, given the diverse control needs worldwide and the varying development processes and content of control programs, this paper focuses on proposing a control zoning program based on established national policies and mature evaluation methods in China. In subsequent research, building upon the twinning framework, data model, and basic software architecture obtained in practical applications, the computational model and platform functions can be enhanced or expanded. Such expansion will facilitate the

swift construction of a digital twin platform tailored to the specific study area.

Conclusion

This paper addresses the digital transformation challenges in rural ecological landscape control through the implementation of intelligent rural control based on the digital twin concept. The digital twin service scenario encompasses monitoring, analysis, strategic solution generation, control behavior implementation, and participant interaction. Through five components—the physical rural ecological landscape entity, twin model, service environment, twin data, and digital platform—the ecological and morphological information associated with the rural ecological–production–living space is effectively intertwined. Data mining and spatial fusion, coupled with the construction of a database, enable the generation of a multitechnology-supported twin platform on a distributed system. Experimental verifications demonstrate the platform's versatility in handling diverse rural ecological landscape control scenarios, expanding the application scope of digital twin technology in the rural domain and providing valuable insights for addressing digital transformation challenges in this context.

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Author contributions
YNC and FQT designed the study. YNC and FQT were major contributors to data collection. FQT developed the formal analysis and software. FQT initiated the idea for the study and was involved in the writing of the original draft. YNC was the principal investigator (PI) for the funding and designed the research ideas. All authors read and approved the final manuscript.

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Availability of data and materials
The data sets used and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Competing interests
No financial or nonfinancial interests have been received or will be received from any party related directly or indirectly to the subject of this article. The authors have no competing interests to declare.

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