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Opportunities and Challenges of Arable Land Red Line Regulation and Monitoring in the Big Data Era: Postprint

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Abstract

The national condition of a large population with limited land determines the necessity for China to implement the world's strictest farmland protection system. Effective, timely, and accurate monitoring of the control status of China's farmland protection red line has become a critical guarantee for achieving farmland protection and food security, while the development of frontier technologies such as remote sensing big data, cloud computing, and artificial intelligence provides new opportunities for farmland control monitoring. This article systematically elaborates on the current research status and challenges in farmland protection red line control monitoring, including the construction of monitoring object systems, the availability of remote sensing data, and the accuracy and timeliness of monitoring results; introduces frontier technologies and application prospects of big data technology in farmland red line monitoring, and proposes innovative technical solutions for farmland red line monitoring; discusses the challenges faced in realizing this research paradigm transformation, and offers corresponding recommendations on issues such as the connotation of farmland protection, the delineation of basic plot units, and the construction of a monitoring network for territorial spatial planning implementation.

Full Text

Preamble

Opportunities and challenges in monitoring cultivated land red line in big data era

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Abstract

China's demographic reality of a large population with limited land resources necessitates the world's most stringent cultivated land protection system. Effective, timely, and accurate monitoring of cultivated land protection red line status is essential for ensuring both cultivated land preservation and national food security. The development of cutting-edge technologies such as remote sensing big data, cloud computing, and artificial intelligence has created new opportunities for cultivated land control and monitoring. This article systematically elaborates on the current research status and challenges in cultivated land protection red line control and monitoring, including the establishment of monitoring object systems, the availability of remote sensing data, and the accuracy and timeliness of monitoring results. It introduces advanced technologies and application prospects of big data technology in cultivated land red line monitoring and proposes innovative technical solutions. The article also discusses challenges facing this research paradigm shift and provides recommendations on the connotations of cultivated land protection, delineation of basic land units, and construction of monitoring networks for implementing national land spatial planning.

Keywords: cultivated land red line, remote sensing monitoring, big data research paradigm, food security

1. Current Status and Existing Problems in Cultivated Land Protection Red Line Control and Monitoring

1.1 Evolution of China's Cultivated Land Protection Red Line Policy and the Importance of Monitoring

Since the founding of the People's Republic of China in 1949, the country has consistently prioritized cultivated land protection and utilization [Figure 1: see

original paper]. This evolution has progressed from initial exploration of cultivated land resources to gradual expansion of quality improvement during the reform and opening-up period, and further to comprehensive system protection since the 18th National Congress of the Communist Party. This developmental trajectory and continuous refinement of policies have formed an integrated cultivated land protection and utilization system that emphasizes not only quantity but also the “trinity” balance of quantity, quality, and ecology, laying a solid foundation for ensuring food security, promoting green and high-quality agricultural development, and accelerating agricultural modernization. Research demonstrates that these cultivated land protection red line policies have played a crucial role, enabling China to feed nearly 20% of the world’s population with less than 9% of global cultivated land.

However, with rapid economic and social development, this vital strategic resource faces increasingly severe protection challenges. According to National Bureau of Statistics data, China’s total cultivated land area decreased by 113 million mu between the second national land survey in 2009 and the third in 2019. Issues such as cultivated land “non-agriculturalization” and “non-grainization” continuously threaten food security, while regional cultivated land quality continues to decline and utilization efficiency remains low. Climate change further compounds these challenges, particularly through rising temperatures, increased precipitation variability, and more frequent extreme climate events such as intensified droughts and floods, which profoundly affect cultivated land stability and sustainability. Under the combined pressures of human activities and climate change, changes in cultivated land control status occur more rapidly, intensely, and complexly, making high-timeliness, accurate, and comprehensive assessment and monitoring an urgent priority.

Traditional monitoring methods suffer from numerous deficiencies, including long cycles, poor timeliness, low accuracy, and high costs, making them inadequate for timely, accurate, and dynamic monitoring requirements. Big data offers advantages in massive data processing, rapid analysis, and intelligent decision-making. By integrating multi-source data such as satellite imagery, meteorological data, and soil monitoring, high-frequency, high-precision multi-dimensional monitoring of cultivated land utilization status can be achieved, providing more accurate data support and new research approaches for monitoring cultivated land red line control status. For example, Google’s Dynamic World platform, built on remote sensing big data and cloud computing, has realized the transformation from static to near real-time land cover mapping, providing an important paradigm for cultivated land red line control status monitoring and early warning.

1.2 Main Problems in Current Cultivated Land Protection Red Line Control and Monitoring

1.2.1 Urgent Need for a Multi-Dimensional Information Monitoring System for Agricultural Land Systems Cultivated land monitoring ob-

jectives and content extend beyond simply quantifying area changes to comprehensively considering multiple dimensions and hierarchical characteristics including quality, cropping systems, ecology, and health. Cultivated land quality encompasses physical and chemical properties such as soil fertility and texture. Cropping system monitoring must consider not only technical factors like planting structure, methods, and efficiency, but also economic factors such as socio-economic benefits, market competitiveness, and farmer income. Ecological condition monitoring must evaluate contributions to biodiversity, soil and water conservation, climate regulation, and carbon sequestration, while also considering ecological pressures such as land degradation. Cultivated land health includes aspects like pesticide use, pollutant content, and food safety.

While remote sensing technology has played an important role in monitoring cultivated land area, monitoring other dimensions requires coupling remote sensing with multi-modal data for collaborative observation. For instance, monitoring cultivated land quality and erosion conditions demands higher spectral and spatial resolution data and more advanced algorithms, combined with ground station observations to strengthen multi-source collaborative observation technologies in multi-dimensional cultivated land information monitoring.

1.2.2 Abundant Satellite Remote Sensing Data but Low Consistency and Need for Standardization Since the 21st century, China conducted its second and third national land surveys in 2007 and 2019, respectively. The published cultivated land areas were 2.031 billion mu and 1.918 billion mu, released as statistical data at the district/county administrative level. These data are considered the most accurate, authoritative, and legally valid. However, due to relevant legal regulations, the original parcel data from these surveys have not been made public, leaving open-source satellite remote sensing data products developed by research institutions as the primary data source for scientific research.

Since the free sharing of medium- and high-spatial-resolution satellite data—such as the U.S. Landsat series in 2008, European Sentinel series in 2014, and China's Gaofen data in 2019—massive open-source data have become the main source for remote sensing-based cultivated land mapping. Additionally, remote sensing cloud computing platforms represented by Google since 2012 have become the preferred computing platforms for cultivated land remote sensing monitoring, featuring integrated multi-source data, parallel computing, and free access for research groups. The emergence of remote sensing big data and cloud computing platforms has greatly promoted the development of medium-resolution global land cover data products, with more than 10 sets of cultivated land remote sensing monitoring products for China in 2020 .

However, these datasets exhibit significant inconsistency and uncertainty. Among 12 cultivated land remote sensing datasets for China in 2020, over 53.55% of regions show low consistency (where fewer than 5 products agree), covering an area of 1.9025 million km² [Figure 2: see original paper]. Fully

consistent regions (where all 12 products identify cultivated land) account for only 12.89% (457,900 km²). High-consistency areas are mainly distributed in traditional agricultural regions with flat terrain and concentrated cultivated land, such as the Northeast Plain, North China Plain, and Middle-Lower Yangtze Plain. In contrast, multiple datasets show greater inconsistency in fragmented cultivated land areas such as the Gobi region north of the Inner Mongolia farming-pastoral ecotone, the Qinghai-Tibet Plateau, southern hilly areas, and the Hengduan Mountains. While the overall area from the 12 products shows strong consistency with the third national land survey, significant regional differences remain. Therefore, future satellite remote sensing monitoring of cultivated land red lines urgently requires strengthened industry standard development to improve data standardization.

1.2.3 Need for Deepened Integration Between Research and Industry Sectors, and Enhanced Data Sharing Although automated classification technologies have made significant progress in scientific research, natural resources departments still require substantial manual intervention or completely manual interpretation for practical applications such as cultivated land illegal occupation monitoring. Due to significant seasonal and regional differences in cultivated land background coverage, and the diversity of illegal structures in category, size, color, and morphology, traditional AI-based target detection algorithms often suffer from omission and commission errors when applied to law enforcement scenarios. However, manual interpretation also suffers from poor timeliness, low efficiency, high labor costs, and accuracy that is difficult to guarantee due to operator experience.

Currently, China's cultivated land red line monitoring has made important progress in both scientific research and industry applications. In scientific research, numerous remote sensing monitoring datasets have been published, including "10 m resolution main crop distribution dataset for Northeast China," "500 m resolution irrigated cultivated land distribution dataset for China," "1 km resolution phenological dataset for staple crops in China," and "30 m resolution winter wheat planting distribution dataset." However, better integration of scientific advances with agricultural and natural resources departments still requires enhanced collaboration between researchers and government personnel.

In terms of cultivated land data surveys, industry departments have invested substantial resources. For example, the Ministry of Natural Resources conducts national land use status surveys approximately every 10 years, with the second and third surveys producing high-precision, authoritative data products. The Ministry of Agriculture and Rural Affairs has organized national cultivated land quality monitoring since 2008. However, these surveys only provide statistical reports without releasing original data. To better coordinate resources and deepen the potential of scientific research and departmental applications, it is necessary to break "data silos" and further coordinate data sharing and openness

between business departments and research institutions.

Earth science data sharing is particularly important for addressing today's most challenging and unprecedented global environmental issues and achieving the UN 2030 Sustainable Development Goals. The U.S. Department of Agriculture's Natural Resources Inventory (NRI) program, including land use, soil characteristics, and water quality information, is updated every five years with public data access. The EU's LUCAS project, launched in 2006, conducts surveys every three years across 28 member states to obtain land cover and use statistics, which are publicly released. The European Space Agency provides open access to some coarser resolution remote sensing images like 10 m Sentinel-2 data, though higher-resolution commercial satellite imagery at 0.5-1 m resolution remains not fully free. Investigating these countries' data sharing scopes, formats, and legal mechanisms is important for China's cultivated land monitoring data coordination, resource conservation, and efficient utilization.

2. Big Data Research Paradigm for Cultivated Land Protection Red Line Control and Monitoring

2.1 "Remote Sensing Big Data + Cloud Computing + AI" Technical System

In recent years, China has successfully launched Gaofen and Ziyuan series earth observation satellites, supplemented by commercial microsattellites and UAV imagery, obtaining massive high spatiotemporal resolution data on cultivated land systems. Coordinated with foreign remote sensing data, this provides data support for real-time monitoring and early warning of cultivated land red line control status. Meanwhile, remote sensing cloud computing platforms offer unprecedented opportunities for mining remote sensing big data, overcoming traditional limitations such as high hardware costs, slow software updates, and difficult data sharing to achieve rapid data acquisition, real-time processing, and online services.

Artificial intelligence technology can process satellite images or aerial photographs to automatically identify and monitor agricultural land changes such as illegal occupation and cultivated land expansion, regularly checking land use status and issuing warnings for violations. AI can also monitor cultivated land health, including soil quality, crop growth, and water resource utilization, helping farmers better plan and manage their operations. Therefore, the integration of remote sensing big data, cloud computing, and AI can acquire high-precision cultivated land data over large areas in real time, including multi-dimensional information on quantity, quality, and ecological status, thereby supporting multi-dimensional information monitoring of cultivated land systems [Figure 3: see original paper].

2.2 Applications of the Big Data Research Paradigm

2.2.1 Real-Time Monitoring and Early Warning of Cultivated Land Red Line Control Status Current monitoring cycles for cultivated land red line control status are primarily annual, which cannot meet the needs of dynamic regulation. Multi-modal remote sensing, cloud computing, and AI technologies can enable automated, real-time identification of high-precision territorial elements to serve real-time monitoring and early warning. Advances in algorithms within high-performance open-source software frameworks like TensorFlow, combined with cloud computing platforms' data collection and processing capabilities, create opportunities for higher spatial and temporal resolution cultivated land datasets.

A key research focus is developing rapid identification technologies for disturbance activities within red line ranges. Addressing the challenge of quickly and accurately obtaining natural and human disturbance information requires constructing sample libraries of surface disturbance elements such as construction occupation, reclamation and planting, disaster damage, illegal logging, and non-grain conversion, using high-resolution, multi-angle, multi-mode optical, hyperspectral, and radar data. By developing intelligent adaptation methods for diverse scenario spatial red line control element models in multi-source, wide-area demonstration zones, rapid and accurate extraction and identification of key elements for cultivated land red line safety baseline control can be achieved.

Cultivated land red line assessment and early warning technologies include constructing evaluation index systems for quantity, quality, and pattern, and establishing assessment and early warning model tools. Building multi-dimensional evaluation index systems that integrate quantity, quality, ecology, pattern, potential, and use, along with risk assessment and early warning models for cultivated land red line control oriented toward national food security, enables rapid assessment and precise early warning of control risks.

Currently, passive monitoring driven by media reports and public opinion remains common, making proactive monitoring difficult. Future research must further improve target detection algorithms in combination with AI, considering more regional characteristics and background information to develop more intelligent algorithms that can handle the diversity and complexity of cultivated land violation monitoring, further reduce manual intervention, improve law enforcement efficiency and accuracy, and ultimately achieve proactive and precise monitoring for cultivated land protection.

2.2.2 Reconstructing Historical Evolution Processes of Cultivated Land Status Reconstructing cultivated land evolution processes for different historical periods requires different data sources and methods. For the period since 2000, periodic satellite-based cultivated land resource survey and monitoring technologies are relatively mature, primarily relying on medium- and high-resolution multi-source remote sensing data such as Landsat (30 m),

Sentinel-2 (10 m), PlanetScope (3-5 m), and domestic Gaofen satellites (0.8-10 m). Long time-series multi-source remote sensing datasets are reconstructed through data fusion, cloud and noise removal, data interpolation, and filtering smoothing, followed by remote sensing image classification using machine learning and deep learning algorithms to reconstruct historical evolution processes since 2000.

For periods before 2000, reconstruction primarily relies on remote sensing data combined with agricultural statistical data (e.g., area, yield) to infer historical cultivated land distribution through crop spatial allocation models (SPAM). Based on reconstructed long time-series datasets, change detection methods like Landtrendr can identify key inflection points and hotspot areas of cultivated land change to analyze spatiotemporal succession patterns.

2.2.3 Rapid Assessment of Extreme Weather Disaster Impacts on Cultivated Land

Extreme weather disaster impact assessment includes rapid disaster monitoring and forecasting, and impact evaluation. First, “remote sensing big data + cloud computing + AI” provides important data and methodological support for disaster monitoring and forecasting. Hao et al. combined multi-source satellite data to propose optimized meteorological drought index (OMDI) and optimized vegetation drought index (OVDI) for monitoring long-term spatiotemporal patterns of drought in Southwest China. By training deep neural networks to capture relationships between input (reanalysis weather data at a given time) and output (reanalysis weather data at target time), weather disaster forecasting speed can be improved by several orders of magnitude compared to numerical weather prediction methods. Huawei’s Cloud Tianqi team developed the “Pangu-Weather” AI weather forecasting system, which shows significant advantages in typhoon path prediction accuracy across different regions, tropical storm intensities, and forecast times compared to ECMWF HRES. Zhang et al. proposed NowcastNet, an extreme precipitation nowcasting model that couples physical laws with deep learning to achieve accurate forecasting of different rainfall rates, particularly extreme events previously difficult to handle.

Second, remote sensing technology can comprehensively and timely evaluate cultivated land conditions after disasters. Using high-performance computing power from cloud platforms combined with AI algorithms to analyze remote sensing big data, disaster impact characteristics such as affected cultivated land area and crop losses can be identified. Chen et al. accurately characterized flood impacts on cultivated land in the Middle-Lower Yangtze River basin in 2020 by combining remote sensing cloud platforms with change detection methods. Javed et al. explored potential links between agricultural drought and yield losses of winter wheat and summer maize, finding that increased frequency of extreme drought events is an important reason for significant yield declines in North China. Dong et al. assessed impacts of three typhoons (“Bavi,” “Maysak,” and “Haishen”) on crops in Northeast China using normalized difference infrared index (NDII) and disturbance index (DI), providing scientific guidance for post-

disaster farmland management.

3. Recommendations and Outlook

3.1 Developing a Multi-Dimensional “Area-Quality-Ecology-Health” Cultivated Land Information Monitoring System

Current cultivated land monitoring research primarily focuses on area changes. However, given modern agriculture’s complexity, multi-dimensional monitoring is crucial. Key dimensions should include cultivated land quality, crop planting structure, management practices, ecological conditions, and health status. This comprehensive multi-dimensional monitoring helps deepen understanding of land resources and provides more accurate and comprehensive data support for scientific land management. Understanding cultivated land quality and health helps farmers adopt more effective management measures, while monitoring changes in crop structure and management practices can support agricultural policy formulation and promote sustainable practices.

3.2 Strengthening Domestic Satellites and Cloud Computing Platforms for Cultivated Land Monitoring

Increasingly abundant medium- and high-resolution remote sensing data, fused into higher-dimensional spatial, spectral, and temporal remote sensing data cubes, can enhance feature extraction and data mining capabilities to overcome key technical bottlenecks in cultivated land system remote sensing monitoring. Future efforts should improve the domestic land remote sensing satellite observation system by increasing the number of launched and in-orbit satellites, continuously improving the “Ziyuan” and “Gaofen” series, and enhancing data accuracy and reliability. Adding bands that reflect crop spectral characteristics, particularly “red-edge” bands that effectively capture unique crop spectral features, can improve monitoring accuracy for crop growth and pest diseases.

The “Jilin-1” satellite constellation from Chang Guang Satellite is a notable example, with 108 satellites currently in orbit achieving 35–37 sub-meter-level revisits per day for any location globally, showing important application prospects for time-sensitive scenarios like illegal occupation monitoring. Future efforts should emphasize coordinated utilization of domestic land resource satellites and commercial satellite big data to better support objective, accurate, and real-time monitoring of cultivated land and other natural resource elements.

3.3 Strengthening Construction of Key Basic Information Databases Such as Basic Parcel Units to Improve Monitoring Accuracy

Pixel-based classification methods often fail to fully exploit spatial information from neighboring pixels, causing classification errors and “salt-and-pepper” noise. Integrating basic parcel unit information into remote sensing monitoring and constructing cultivated land basic parcel databases can significantly improve

accuracy and reduce errors. Parcel information serves as a bridge connecting remote sensing monitoring with practical agricultural applications and should be integrated with data sharing from agriculture and natural resources departments.

Using high-resolution remote sensing imagery and advanced image classification and segmentation techniques, supplemented by field surveys, precise parcel identification can be achieved through edge detection or spatial information aggregation. However, parcel information extraction still faces challenges in high-resolution data accessibility, extraction in complex landscapes, and large-scale continuous monitoring.

3.4 Promoting Efficient Data Interoperability and Collaboration Between Scientific Research and Departmental Operations

Coordinating and sharing cultivated land scientific monitoring data with departmental operational data based on standardized specifications can play a key role in improving agricultural management efficiency and disaster risk response. While important progress has been made in cultivated land data sharing both domestically and internationally, the balance between open sharing and security protection requires dedicated government departments or research institutions to coordinate overall efforts. Data sharing standards and metadata specifications must be established to ensure security, format, content annotation, and quality control comply with regulations. Clear user application processes should be developed where researchers apply according to specifications, responsible departments review and approve, and data use agreements are signed to prevent misuse and ensure data security.

3.5 Integrating Cultivated Land Protection Red Line Control and Monitoring into the Territorial Spatial Planning Monitoring System (CSPON)

Integrated cultivated land monitoring platform construction can promote agricultural digitalization, intelligence, and precision, comprehensively monitoring cultivated land quality changes and grain production dynamics to scientifically warn and ensure national food security. China is advancing the construction of the Territorial Spatial Planning Implementation Monitoring Network (CSPON) to address unified network architecture, algorithm models, and data governance issues in territorial spatial planning implementation monitoring, and to improve foundational policy standards for data sharing. Cultivated land red line control status monitoring is an important component of this system. Remote sensing big data and cloud computing not only enrich planning implementation monitoring methodologies but also provide valuable opportunities for constructing new theories and monitoring systems for territorial spatial planning supervision. It is necessary to re-examine monitoring objectives, indicators, methods, and evaluation systems, combining technological innovation with planning practice to

create more accurate, efficient, and sustainable new mechanisms for territorial spatial planning implementation monitoring.

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