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Agricultural land and environmental risks: Evidence, assessment and conservation transition

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Published in
Frontiers in Environmental Science

ISSN 1664-8714
ISBN 978-2-8325-4398-6
DOI 10.3389/978-2-8325-4398-6

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Agricultural land and environmental risks: Evidence, assessment and conservation transition

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Citation
Kong, X., Ke, X., Tóth, G., Tan, M., eds. (2024). *Agricultural land and environmental risks: Evidence, assessment and conservation transition*.
Lausanne: Frontiers Media SA. doi: 10.3389/978-2-8325-4398-6

Table of contents

TYPE Editorial
PUBLISHED 19 January 2024
DOI 10.3389/fenvs.2024.1365478

Check for updates

OPEN ACCESS

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RECEIVED 04 January 2024
ACCEPTED 08 January 2024
PUBLISHED 19 January 2024

CITATION
Kong X, Zhao Z, Lei M, Tan M, Ke X and Tóth G (2024), Editorial: Agricultural land and environmental risks: evidences, assessment and conservation transition.
Front. Environ. Sci. 12:1365478.
doi: 10.3389/fenvs.2024.1365478

Editorial: Agricultural land and environmental risks: evidences, assessment and conservation transition

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KEYWORDS
agricultural land, environmental risks, risk assessment, sustainable transformation, mechanism

Editorial on the Research Topic
Agricultural land and environmental risks: evidences, assessment and conservation transition

Introduction

Meeting increasing food demands in an environmentally sustainable manner is a worldwide challenge. Agricultural land covers 38% of the world's land area and produces about 30% of the world's net primary products to meet human needs (Ramankutty et al., 2008; Food and Agriculture Organization of the United Nations, 2023). It is the expansion and intensification of agricultural land that has driven the huge increase in global food production over the past few decades, which is a crucial way to achieve the "zero hunger" goal of the United Nations (UN). However, high-intensity use and uncontrolled expansion of agricultural land have caused many environmental problems, like overexploitation of groundwater (Mishra et al., 2014), greenhouse gas emissions (Rehman et al., 2021), biodiversity loss (Kehoe et al., 2015), and serious nitrogen or phosphorus pollution (Li et al., 2022). Unsustainable agricultural land use beyond the environmental limits affects the stability of the natural system. Therefore, how to increase food production sustainably while reducing the environmental impact has become a global issue that should be considered for realizing Sustainable Development Goals.

Given the significance of sustainable agricultural land use for global food security, our Research Topic seeks to bring together perspectives and empirical studies of environmental risk management related to sustainable agricultural land use. There are 14 articles on this Research Topic. Specifically, more research focused on agricultural land risk assessment (four articles), environmental risk generation process and mechanism of agricultural land use (six articles), and sustainable agricultural land utilization transformation and policy optimization (three articles). The Research Topic is far from enough to understand agricultural land use and environmental risks. We aim to attract more researchers to pay more attention to agricultural land use transition and environmental risk management.

Zhao et al. systematically explored agricultural land risk, analyzing 12,581 literature sources using CiteSpace. It showed that two phases (2002–2015 and 2015–2022) revealing evolving research hotspots. The initial phase focused on diverse risks (soil, nitrogen, sewage sludge), emphasizing theoretical frameworks in intensification and transport protection. The subsequent phase delved into mechanisms, covering methodologies, source analysis, toxic elements, and random forest analysis. The study highlighted three key steps to mitigate risk were outlined: stringent land use management, sustainable agricultural practices, and robust environmental governance. The findings significantly contributes the theoretical foundation of sustainable land management, providing valuable insights for mitigating hazards in evolving land use scenarios.

Agricultural land risk assessment

Du et al. established the evaluation system of the GUL-CL from four aspects (environmental friendliness, resource conservation, spatial intensification, and output efficiency) in the Heilongjiang reclamation area. The results show that the degree of GUL-CL in the study area is generally well-developed. The coupling coordination degree of green use of agricultural land (GU-CL) (0.20–0.50) is at a low coupling coordination stage. This study can provide practical knowledge for the sustainable use of agricultural land in the black soil region of Northeast China. This study can provide practical knowledge for the GU-CL in the black soil region of Northeast China.

Wei et al. studied urbanization's spatiotemporal evolution and agricultural land use coordination in Hunan Province (2000–2018). They identified current coordination types and proposed optimization measures. Results showed a transition from severely uncoordinated to ultimately coordinated development. Hunan's coordination pattern, with eight sub-regions, requires expedited factor flows through reforms and innovative mechanisms for each type to address developmental shortcomings. This study serves as a scientific reference for effectively implementing coordinated development strategies in major food-producing regions.

He et al. conducted a visual analysis to comprehensively review the progress in ecological security assessment of agricultural land. They examined concepts, characteristics, driving factors, assessment scales and methods, technologies, and simulation methods in relevant literature. Results show that research on the ecological security of agricultural land is in its early stages, lacking a comprehensive exploration. Current investigations focus on situational analyses, with a deficiency in simulation-based dynamic analyses of driving mechanisms. Future research should explore intricate driving mechanisms in socio-economic-ecosystem interactions, emphasizing comprehensive models for dynamic spatial and multiscale ecological security assessment. This contributes insights for theoretical advancements and land-use plans to mitigate global climate change.

Li et al. emphasized the importance of mutual matching of underground root systems for forming functional plant communities during vegetation restoration. They employed the "Amoeba graphic method" to establish the Root System Framework Index (RFI) based on root system morphology, quantitative, and spatial connectivity features. Monitoring alfalfa (T-type), fescue (F-type), and a mixed planting (T + F-type) revealed RFI parameters (effectiveness coefficient, root density, framework degree, and soil bulk density). RFI values for T, F, and T + F were 0. 38, 0.86, and 1.68, respectively, effectively representing root structural characteristics. The study supports ecological construction and assessment for restoring damaged vegetation.

Process and mechanism of agricultural land risks

Wang et al. assessed natural quality, spatial distribution, and land use intensity on the Qinghai-Tibet Plateau at the county level, determining land use models. They discussed optimization directions considering ecological conservation and agricultural and pastoral regulation. The "NUS" three-dimensional model accurately reflected Qinghai-Tibet Plateau land use characteristics. Current patterns align with ecological conservation zones, but issues of irrational expansion and excessive utilization exist in transitional zones. Agricultural land utilization and optimization should prioritize ecological security, addressing conflicts for sustainable land use on the Qinghai-Tibet Plateau.

Hu et al. studied orchard expansion in Fuxian, Luochuan, and Huangling counties in Shaanxi Province from 1990 to 2020. Orchard data were extracted using Linear Spectral Mixture Analysis (LSMA) and decision trees for cash crop identification. Spatiotemporal dynamics were quantitatively analyzed using spatial geometric center displacement, geographic features, landscape patterns, and orchard suitability. A machine learning approach, random forest regression, identified driving forces. Continuous expansion, most rapid from 1990 to 2005, occurred toward north-central regions and highly suitable areas, with increased cohesion. Slope emerged as the primary factor influencing orchard expansion.

Hua and Li used Chinese Family Panel Studies (CFPS) data from 5,133 households in 2014 and 3,810 households in 2018. They applied Propensity Score Matching with Difference-in-Differences (PSM-DID) and Kernel Heteroskedasticity-Based (KHB) models to investigate the impact of land loss on academic performance among rural adolescents. Results indicate that adolescents from households experiencing land loss exhibit poorer academic performance and lower awareness of education value compared to those without land loss. The identified logical mechanism is "land loss → family educational cognition → family human capital investment → adolescent academic performance." Gender differences show a greater negative impact on boys' academic performance due to land loss. The government should enhance training for land-loss farmers, improve social security for female-led families, and prioritize support for boys affected by land loss.

Xie et al. surveyed Wannian County to analyze the causes and risks of compensatory cultivated land (CCL) migration to mountainous areas at a micro level. They used Boosted Regression Tree (BRT) models and a grain production capacity assessment model. Results show CCL shifting uphill (2010–2020) with notable fragmentation, and a 14.77% abandonment rate for agricultural land. Site conditions (elevation, plot area, cultivated land continuity) explain abandonment reasons. Abandonment led to a risk of losing 297. 48 tons of grain production capacity. Spatial mismatch resulted from neglecting coupled relationships between site conditions, utilization status, and functional requirements. A proposed solution is Natural Resource Requisition-Compensation Balance (NRRB), involving spatial displacement for abandoned CCL in uphill areas and cultivable forest land in submountainous regions, optimizing the land use pattern toward Feng Tunning's agricultural circle.

Liang and Geng investigated soil samples pre and post no-grain canal (NGC) implementation in rice paddies in Zhejiang Province, China. They measured soil environmental factors, conducted 16S rDNA amplicon sequencing, and analyzed changes in soil bacterial communities and ecosystem functions. Results showed NGC increased the relative abundance of Proteobacteria (27.89%) and Actinobacteria (25.25%). Total bacterial quantity increased in all samples, with significant variations. NGC enhanced α diversity indices (Ace, Chao1, Coverage, and Shannon indices) significantly ($p < 0.01$). Environmental factors associated with soil bacterial diversity and structure were total nitrogen (TN), available phosphorus (AP), pH, soil organic matter (SOM), field water capacity (FIQ), and available potassium (AK). Wilcoxon rank-sum tests indicated NGC significantly enhanced amino acid transport and metabolism functions of soil bacteria. Results suggest NGC benefits soil bacteria diversity, enhances soil ecosystem multifunctionality, and promotes sustainable soil ecosystem conservation in cultivated lands.

Faye et al. used ArcGIS and ENVI software to interpret land use types (2000–2020) and employed a transfer matrix method to characterize agricultural land transformation. Pearson correlation coefficients assessed interrelationships between natural and socio-economic drivers of agricultural land use. Results showed approximately 588.66 square kilometers undergoing agricultural land transformation, with grassland being pivotal. Mont-Rolland had the highest net transformation (33.22%), and Sandiara town had the lowest (−41.73%). Temporal distribution in Koul town was −0. 35%, while Mont-Rolland town was 24.84%. Agricultural land transformation intensity was 11.34% in Malicounda town. Social surveys revealed a strong correlation (0.971) between wind erosion and soil salinity, potential driving factors for agricultural land transformation.

Sustainable transformation and policy optimation of agricultural land utilization

Guan et al. systematically described the morphological characteristics of agricultural land use in various ecological functional zones and analyzed main issues related to agricultural land use in different regions. Proposing regulatory schemes for agricultural land in ecological functional zones, focused on food security, the paper used Mengjin County as a case study for empirical research. Results showed that, guided by the goal of food security, implementing different agricultural land improvement plans based on ecological zones can enhance food security and amplify environmental effects. Land consolidation and ownership adjustment can restore idle agricultural land to food production land, enhancing food supply capacity without damaging the ecological environment. In ecologically important areas, large-scale ecological transformation may impact food security supply. Promoting ecological agriculture resolves the contradiction between food security production and ecological environmental protection. This study provides reference for decision-making on land consolidation in the new era.

Liu et al. studied the impact of mayors and party secretaries in connection with four protected agricultural demonstration areas—Shandong, Jiangsu, Hebei, and Liaoning Provinces—on the expansion of protected agriculture. Using panel data from 314 prefecture-level cities and 1,792 counties (2014–2018), they employed a multidimensional fixed-effects model. Results showed mayors connected to demonstration areas significantly promoted protected agriculture expansion, with a 10.8% higher average scale in their jurisdiction's county-level areas. Party secretaries' impact was not significant. Geographical differences revealed weakened positive impact in economically less developed western regions or unsuitable planting periods (March to June). Leaders connected to Shandong, Liaoning, and Jiangsu Provinces had significantly different but positive impacts on protected agriculture expansion.

Wang et al. using the grain supply and demand balance method, has categorized the 14 regions (cities) in Xinjiang into deficit/surplus areas of agricultural land to accurately determine the actual compensation standards for areas requiring payment and those receiving compensation. The research results reveal that Xinjiang has an overall surplus of agricultural land, with a total surplus area of 271.57 × 104 ha. However, within Xinjiang, there are still some areas experiencing deficits in agricultural land. It was also found that the benchmark land price is a core factor influencing compensation standards. Furthermore, the study proposes adopting diverse forms of compensation, alleviating financial pressure, financing through multiple channels, ensuring funding sources, and establishing policies such as agricultural land protection compensation standards, dynamic measurement platforms, and supervisory and management mechanisms to achieve a long-term compensation mechanism for agricultural land.

Concluding comments

The Research Topic, titled "Agricultural Land and Environmental Risks: Evidences, Assessment and Conservation Transition" thoroughly explores the intricate challenges of managing agricultural land sustainably in response to escalating global demands. This compilation of peer-reviewed articles encompasses various aspects, including the risk factors associated with land use, risk assessment, and the regulatory transformation and optimization of sustainable utilization. The central theme underscores the critical importance of prioritizing risk prevention and control in the sustainable use of agricultural land.

The introduction emphasizes the significant challenge of meeting global food demands sustainably, highlighting the essential role of agricultural land in producing net primary products. While expanding agricultural land is necessary to achieve the United Nations' "zero hunger" goal, the intensive use and uncontrolled expansion of agricultural land can lead to environmental issues. Addressing the risks associated with land use is, therefore, essential to strike a balance for global sustainable development goals.

The thematic section of this Research Topic meticulously analyzes the causes, drivers, and influencing factors of land use risks, leading to a nuanced understanding of challenges and potential solutions. Articles exploring the restoration of damaged vegetation and soil bacteria reveal insightful interactions between crop microstates and land use risks. Additionally, the increasingly apparent positive impact mechanisms of macro policies in controlling land use risks suggest a growing global emphasis on managing agricultural land risks.

Crucially, the issue highlights regional disparities and the profound impact of local context on the quality of agricultural land, emphasizing the need for tailored, context-specific policies. Insights from studies analyzing agricultural land transfer rents, disaster risk management, and the role of land consolidation in mountainous regions underscore the necessity of nuanced policy interventions aligned with local dynamics to ensure food security and sustainable development.

Importantly, this Research Topic underscores the profound impact of regional variations and local contexts on agricultural land risks, emphasizing the need for context-specific research. It highlights differences in regional gaps, risk-driving mechanisms, and optimization control strategies, particularly in developed regions (such as Zhejiang and Hunan provinces) and underdeveloped regions (such as Henan province, the Loess Plateau, and Thiès region in Senegal). The emphasis is on the necessity of optimization control strategies consistent with local dynamics to ensure a balanced development between production and ecological wellbeing.

Overall, safeguarding the sustainable use of agricultural land is critical for future food production. However, the array of risks it faces poses a significant challenge. It is vital to scientifically measure these risks and devise preventive strategies.

Firstly, establishing a stringent land-use control system is essential. This involves regulating cultivated land strictly, prohibiting arbitrary changes and prioritizing the protection of high-quality cultivated land. Second, enhancing soil fertility is crucial. This involves regulating chemical fertilizer and pesticide use to minimize environmental impact and prevent soil degradation. Third, emphasizing the importance of establishing a regular environmental monitoring system is vital. This comprehensive network should be incentivized to encourage agricultural producers adopting eco-friendly practices. Lastly, there is a need of advancing scientific research in the field of agricultural land risk control, develop unified and coordinated policies. It is necessary to establish risk control mechanisms and institutions, and drive the global imperative for sustainable management of land resources.

We extend our sincere appreciation to all the reviewers who contributed to this Research Topic with their invaluable insights, as well as to the Frontiers in Environmental Science Team for their exceptional coordination efforts.

Author contributions

XKo: Writing–original draft, Writing–review and editing, Data curation, Formal Analysis, Investigation, Methodology, Supervision. ZZ: Data curation, Formal Analysis, Investigation, Supervision, Writing–original draft, Writing–review and editing, Methodology. ML: Formal Analysis, Methodology, Software, Writing–review and editing, Writing–original draft. MT: Methodology, Supervision, Writing–review and editing. XKe: Methodology, Supervision, Writing–review and editing. GT: Methodology, Supervision, Writing–review and editing.

Funding

The author(s) declare financial support was received for the research, authorship, and/or publication of this article. This work was supported by the Chinese Social Science Foundation (19ZDA096), the Chinese National Natural Science Foundation (42171289 and 42201285). China Postdoctoral Science Foundation (2023M733781); Ministry of Science and Technology of the People's Republic of China (2021FY100403).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 04 January 2023
DOI 10.3389/fenvs.2022.1055291

Research on compensation standards for cultivated land protection based on a value-added benefit model in Xinjiang, China

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SPECIALTY SECTION
This article was submitted to Land Use Dynamics,
a section of the journal
Frontiers in Environmental Science

RECEIVED 27 September 2022
ACCEPTED 06 December 2022
PUBLISHED 04 January 2023

CITATION
Wang Y, Yan X, Wang L, Xia B, Yang G and Fan Z (2023), Research on compensation standards for cultivated land protection based on a value-added benefit model in Xinjiang, China.
Front. Environ. Sci. 10:1055291.
doi: 10.3389/fenvs.2022.1055291

This study examines the content of the compensation standard measurement for cultivated land protection to effectively address the imbalance between local economic development and cultivated land protection. The empirical analysis relies on a value-added benefit model. Using the grain supply and demand balance method, 14 prefectures (cities) in Xinjiang were divided into cultivated land deficit/surplus areas, and based on the theory of value-added benefits of converting cultivated land to construction land, a compensation standard measurement system for cultivated land protection was established, and correction coefficients such as potential urban development intensity and government payment capacity were introduced to accurately determine the realistic compensation standard for cultivated land protection in areas that are paid and receive compensation. The results of the study found that the total surplus area of cultivated land in Xinjiang is 271.57×10^4 hm^2, which is in surplus overall, while within Xinjiang, four states (cities) are cultivated land deficit areas, which are also the areas that need to pay compensation amounts, and 10 states (cities) are cultivated land surplus areas, which receive compensation payments. The average compensation standard for cultivated land protection in Xinjiang is 24.27×10^4 RMB/hm^2, while the compensation standard for cultivated land protection in each state (city) is mainly influenced by the benchmark land price and the comprehensive value of cultivated land, of which the benchmark land price is the core factor affecting the compensation standard. In terms of the total amount of compensation, the total amount of compensation paid for cultivated land protection in Xinjiang is $5,323.93 \times 10^8$ RMB, which is paid by the provinces where cultivated land is scarce, and in terms of the provinces, by the four compensation areas to the remaining 10 reimbursement areas, for which we put forward policy suggestions such as adopting diversified forms of compensation, alleviating financial pressure, financing through multiple channels, securing sources of funding, establishing cultivated land protection compensation standards, dynamic measurement platforms, and supervision and management mechanisms to realize long-term compensation mechanisms for cultivated land. The study is conducive to clarifying the rights and responsibilities of cultivated land protection, mobilizing the motivation of the main actors in cultivated land protection, and promoting balance and harmony between regional economic development and cultivated land protection.

KEYWORDS

value-added benefit measurement model, cultivated land protection, compensation standard, value of cultivated land, Xinjiang

1 Introduction

Cultivated land is an important strategic resource to ensure food security and maintain social stability. To limit the conversion of large amounts of agricultural land, especially cultivated land, into construction land, China has implemented a strict land use control system (Dang et al., 2021). However, since the 1990s, the area of cultivated land in China has decreased rapidly. According to statistics, only from 2009 to 2018, the area of cultivated land in China has decreased by 393,700 hm^2 (Yuan et al., 2021; Cheng et al., 2022). The enthusiasm of cultivated land protection of high cultivated land stakeholders has become an urgent requirement to promote cultivated land protection (Kong et al., 2005; Lu et al., 2022). As the most direct, basic, and main participant, farmers play a particularly important role in land use and cultivated land protection (Liu et al., 2017; Wu et al., 2017). Although China's current cultivated land protection system has formulated normative implementation measures from the legal and institutional aspects, there are many difficulties in the implementation, and there is a lack of an incentive mechanism for cultivated land protectors after the conversion of cultivated land to construction land (Liu et al., 2017; Huang and Ke, 2020). Its actual value is much higher than the amount of land requisition compensation at that time, which greatly weakens the farmers' awareness of protecting cultivated land (Wu et al., 2017). Scientifically determining the compensation standard of cultivated land is an important way to enhance farmers' awareness of protecting cultivated land and to improve the efficiency of cultivated land protection (Zhong et al., 2012; Zhang and Han, 2018; Zhou et al., 2021).

The academic research on the compensation standard of cultivated land protection is roughly divided into three categories: external benefits based on cultivated land protection, opportunities and input costs based on cultivated land protectors, and value-added benefits based on cultivated land conversion to construction land (Yong and Zhang, 2012). The external benefits of cultivated land conservation refer to the corresponding economic compensation to farmers who cannot enjoy the social and ecological exogenous functions generated by cultivated land in the process of production and use (Jin and Du, 2013), and its value is usually measured using the conditional value assessment method (CVM) (Chaudhry et al., 2007; Dorfman et al., 2009; Jin et al., 2018; Lu et al., 2021), the characteristic value analysis method, and the choice test model method (Rolfe et al., 2002; Campbell, 2007; Johnston and Duke, 2007). As the measurement methods are assessed through subjective human perceptions, their results also differ significantly from the actual compensation capacity (Dahal et al., 2018). Opportunities and input costs of cultivated land protectors refer to the sum of the direct input costs of cultivated land protectors to protect cultivated land and the opportunity costs generated by giving up the best use to compensate, which is in line with the behavior of market subjects and objectives (Xia et al., 2020). However, the cultivated land protection compensation scheme constructed with this idea is mainly a direct subsidy from the government to the farmers, which may have problems, such as limited subsidy, scattered subsidy funds, and an inconspicuous effect of cultivated land protection (Zhou et al., 2019). Based on the value-added benefit of converting cultivated land into construction land, which refers to the difference between the value generated by converting cultivated land into construction land and the income from the use of cultivated land for agricultural production (Wang et al., 2021), the compensation value standard of cultivated land measured by this method can solve the problem of uneven income and compensation brought about by land acquisition (Zhang et al., 2018), better highlight the asset attributes of cultivated land, realize the market value of cultivated land, and also conform to the behavior of market economic agents. It provides objectivity and practical operability.

At present, there is no unified standard for measuring the value-added benefits of converting farmland to construction land. Scholars have measured the value-added benefits of converting farmland to construction land from the perspectives of future value-added returns of farmland (Zhang et al., 2008), the value of similar property rights with the same value components in the modified market (Wen et al., 2021), factors affecting value-added benefits (Liu et al., 2020), and willingness to pay (Yang et al., 2019; Peng et al., 2021; Hu et al., 2022). These measurement methods are either complex or difficult to operate. In addition, the research area needs to be expanded. At present, most scholars are concentrated in central and eastern China, while there is little research on the compensation standard of cultivated land in northwest China, especially in Xinjiang. Xinjiang is not only an important ecological security barrier area in China but also a strategic hub area for national development. Its economic and social development is lagging behind, and the contradiction between cultivated land protection and economic development is prominent. In order to solve the problem of unbalanced development and cultivated land protection, it is particularly important to determine the compensation standard of cultivated land protection in Xinjiang.

Based on this, this paper takes 14 states (cities) in Xinjiang as the research objects to supplement the research on compensation standards for cultivated land protection in the northwest region and, on the basis of accounting for the surplus and deficit cultivated land in each state (city), delineates the compensated and reimbursed areas of cultivated land compensation and uses the theory of value-added benefits of converting cultivated land to construction land as the basis. Based on the theory of value-added benefits of converting cultivated land to construction land, the study attempts to construct a value-added benefits measurement model and introduce compensation correction factors to assess the actual value-added benefits of converting cultivated land to construction land in the 14 states (cities) to improve the farmland protection efficiency of farmers, promote the coordinated development of regional economic development and farmland protection, and provide theoretical reference and decision-making reference for the establishment of farmland protection compensation mechanism.

In this study, we aimed to answer the following questions: 1) Is our proposed value-added benefit model applicable to measuring compensation standards for cultivated land protection? 2) What are the compensation standards for cultivated land protection in different regions in Xinjiang? 3) Apart from the payment of compensation, what other ways are there to compensate for the work of cultivated land protection?

2 Materials and methods

2.1 Study area

The Xinjiang Uygur Autonomous Region, referred to as Xinjiang, is located in the northwestern border of China, between 73°40′E–96°18′E and 34°25′N–48°10′N. It is the largest provincial administrative region in China with an area of 1.66 million square kilometers, accounting for one-sixth of the total land area of China. Xinjiang is a typical temperate continental arid climate with rare precipitation and large evaporation, with an average annual precipitation of 170.6 mm. The existing cultivated land area is 7.86343 million mu, the woodland area is 134 million mu, and the grassland area is 748 million mu, which is one of the five major pastoral areas in China. Xinjiang has 14 states (cities), i.e., five autonomous states, five regions, and four prefecture-level cities in Urumqi, Karamay, Turpan, and Hami (see Figure 1); by the end of 2018, Xinjiang's annual GDP was 1.22 trillion RMB, with 2.487 million permanent residents.

2.2 Data sources

Considering the completeness of the data, this study uses 2018 as the study period. The main data used are as follows: the statistical bulletins on the national economic and social development of 14 states (cities) in Xinjiang in 2018, the 2019 China Statistical Yearbook, the China Urban Statistical Yearbook, the National Compilation of Information on Costs and Benefits of Agricultural Products, the China Agricultural Products Price Adjustment Survey Yearbook, and the Xinjiang Statistical Yearbook. The departmental accounts for the 14 prefectures and cities in Xinjiang, the Natural Resources and Planning Bureau, and the major cities published benchmark land prices and updated assessment results.

2.3 Research methods

The model for measuring the value-added benefits of converting cultivated land to construction land is constructed, in which the compensation and reimbursement areas are defined in terms of food supply and demand. The difference between the net income obtained from converting cultivated land to construction land and the economic, social, and ecological values generated by the agricultural development of cultivated land is taken as the value-added value of converting cultivated land to construction land (Liang et al., 2006; Jiang et al., 2009) (see Figure 2). The compensation and reimbursement areas are combined to finally determine the protection compensation/payment value of cultivated land (Ding and Yao, 2022) so as to lay the foundation for the compensation system for cultivated land protection. This will lay the foundation for the establishment of a farmland protection compensation system. In addition, the value-added benefit of cultivated land converted to construction land in the ideal state is revised by means of a compensation correction factor, making the compensation standard more practical and operable. The studies mentioned above are based on the steady state of cultivated land in Xinjiang; there is no sudden increase/decrease in the number of cultivated lands, and the total crop production does not exist to export and import outside Xinjiang.

2.3.1 Determination of cultivated land surplus and deficit

The regional food supply and demand is used to measure the amount of cultivated land in surplus and deficit and to determine the compensation and reimbursement areas (Li et al., 2014). The

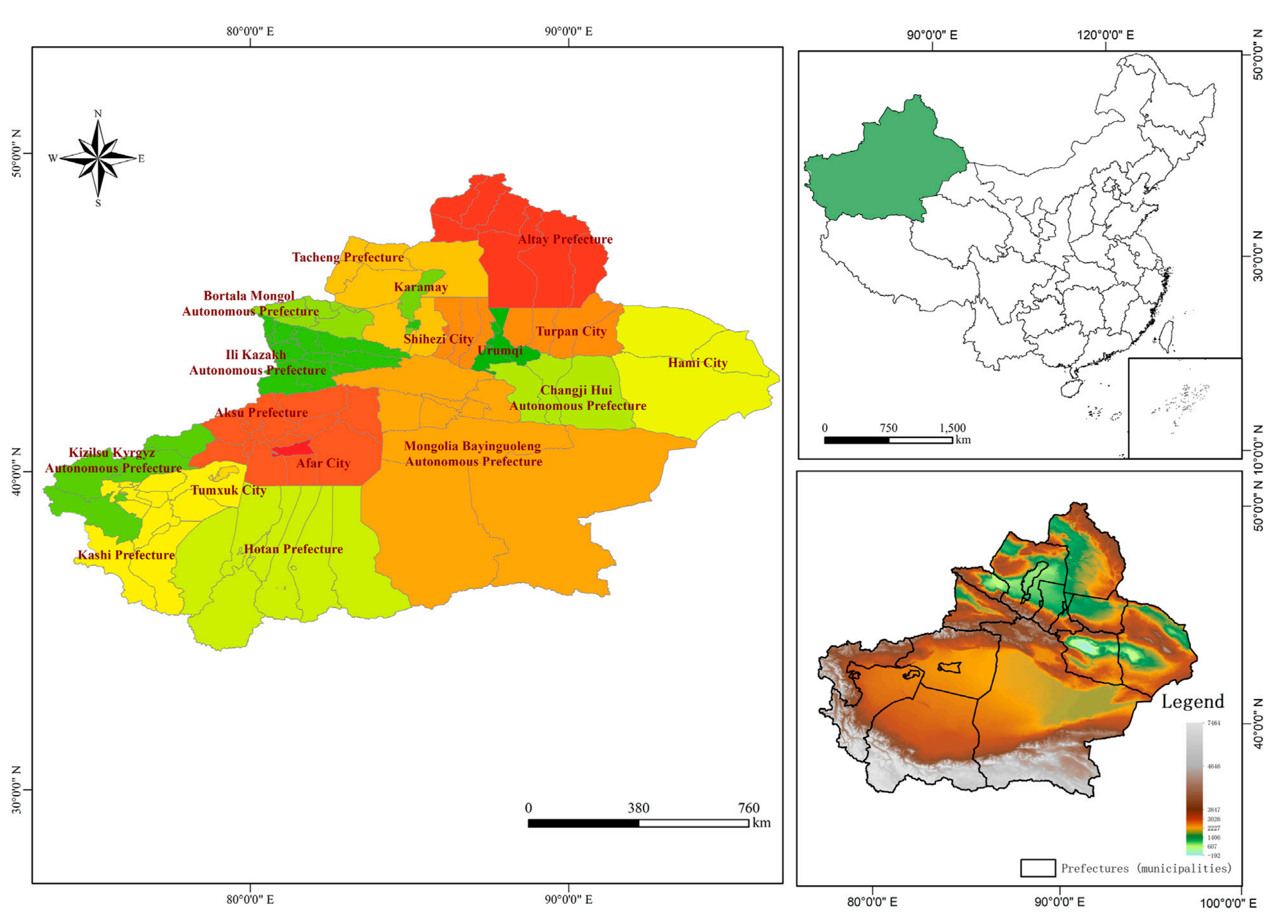

FIGURE 1
Geographic location of the study area.

amount of cultivated land surplus and deficit in different regions are standardized (Zhou, 2005). The specific formula is as follows:

$$Y' = Y_g - Y_x \tag{1}$$

$$Y_x = P_i \times \frac{X_j \times Z}{h_i \times F_i \times D_i} \tag{2}$$

$$Y = \alpha \times Y' \tag{3}$$

$$\alpha_x = \frac{D_i}{D} \times \frac{D_i}{p \times \partial \times F} \tag{4}$$

where Y' is the cultivated land surplus and deficit; Y_g is the amount of cultivated land supply; the cultivated land demand is Y_x; P_i is the demand for cultivated land in region i as a function of the population in that region; D_i is the grain yield; F_i is the replanting index; X_j is the *per capita* food demand; h_i is the food crop ratio; Z is the food self-sufficiency rate; supply is Y_g; Y is the standardized cultivated land surplus and deficit; α is the national grain yield per unit sown area; D is the national grain yield per unit area of the standardized cultivated land; ρ is the national grain yield per unit sown area; and ∂ and F are the grain-sown area share and replanting index, respectively.

2.3.2 Net benefits from the conversion of cultivated land to constructed land

The cultivated land is divided into three categories based on distance from the city: urban cultivated land, suburban cultivated land, and remote cultivated land (Zhang et al., 2018). According to the principle of the location theory (Lin et al., 2017), the closer to the city center, the higher the land price, and the net income from converting these three categories of cultivated land into construction land is measured according to the comprehensive benchmark land price issued by the city, county, and township levels (Zhang et al., 2018). The ratio of the area of cultivated land in the urban area, cultivated land in the suburbs, and remote cultivated land is obtained according to the ratio of cultivated land in areas with similar or the same benchmark land price to the total cultivated land area, which is about 1:2:5 in Xinjiang. The specific formula is as follows:

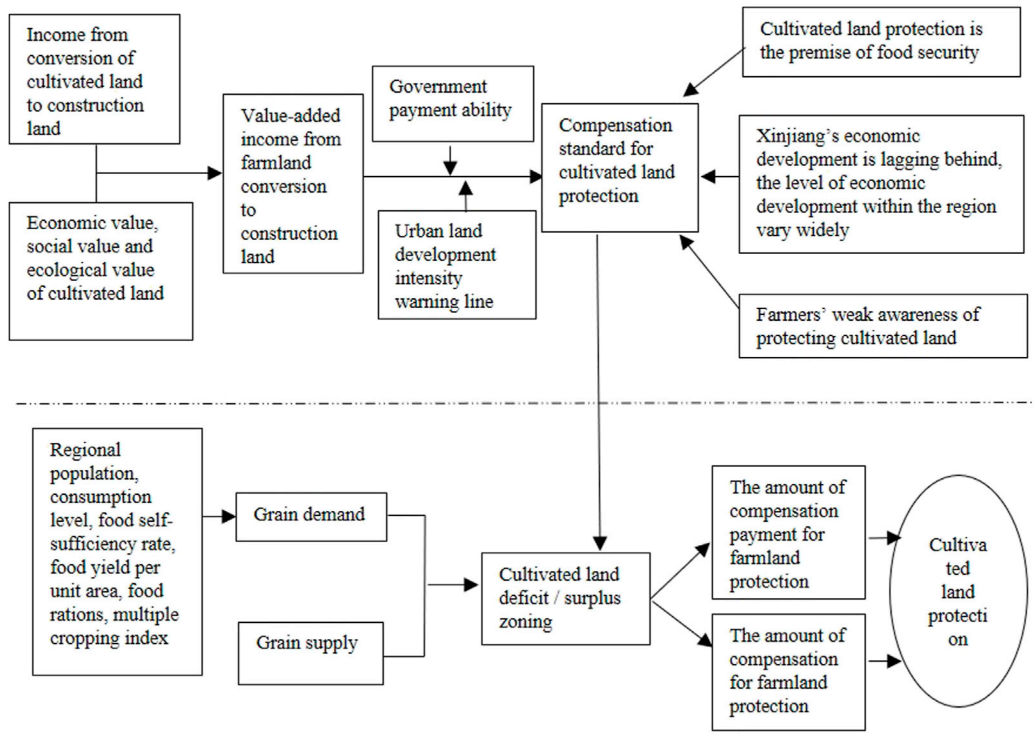

FIGURE 2
Value-added benefit measurement model.

$$V_{gJ} = V_a + V_b + V_c, \quad (5)$$

$$V_{gJ} = \frac{1}{8}v_a + \frac{2}{8}v_b + \frac{5}{8}v_c, \quad (6)$$

where V_{gJ} is the value of cultivated land converted to constructed land; V_a, V_b, and V_c are the values of cultivated land, suburban cultivated land, and remote cultivated land converted to constructed land in the urban–rural intersection, respectively; and v_a, v_b, and v_c are the benchmark land values of cultivated land, suburban cultivated land, and remote cultivated land converted to constructed land in the urban area, respectively.

2.3.3 Net return from the use of cultivated land for agricultural development

1) Economic value of cultivated land resources

The economic value of cultivated land is expressed as income earned in agricultural production, and the best established method of income reduction was chosen to measure (Li et al., 2014; Wang et al., 2020):

$$V_{ec} = \frac{A}{R}\left[1 - \frac{1}{(1+R)^N}\right]. \quad (7)$$

In capturing the net benefit of cultivated land A, the net benefit needs to be corrected to below the normal market, usually expressed as a percentage of the government subsidy to agriculture and farmers (Zhou, 2005).

$$A = A_1 + A_2, \quad (8)$$

$$A_1 = \sum\nolimits_{i=1}^{n} (p_i \times c_i - q_i \times d_i)/S, \quad (9)$$

$$A_2 = 40\% \sum\nolimits_{i=1}^{n} b_i, \quad (10)$$

where A_1 is the net return from cultivated land used for agricultural production; A_2 is the land rent received by farmers in the modified market; p_i denotes the total production of crop i; c_i denotes the unit price of crop i; d_i denotes the unit cost of crop i; 40% is the share of land rent received by the owner of the cultivated land, denoting the total land rent of the cultivated land as a proportion of the total agricultural capital; qi is the crop's sown area; b_i is the unit subsidy given by the government to crop i; and S is the total area of cultivated land.

2) The social value of farmland resources

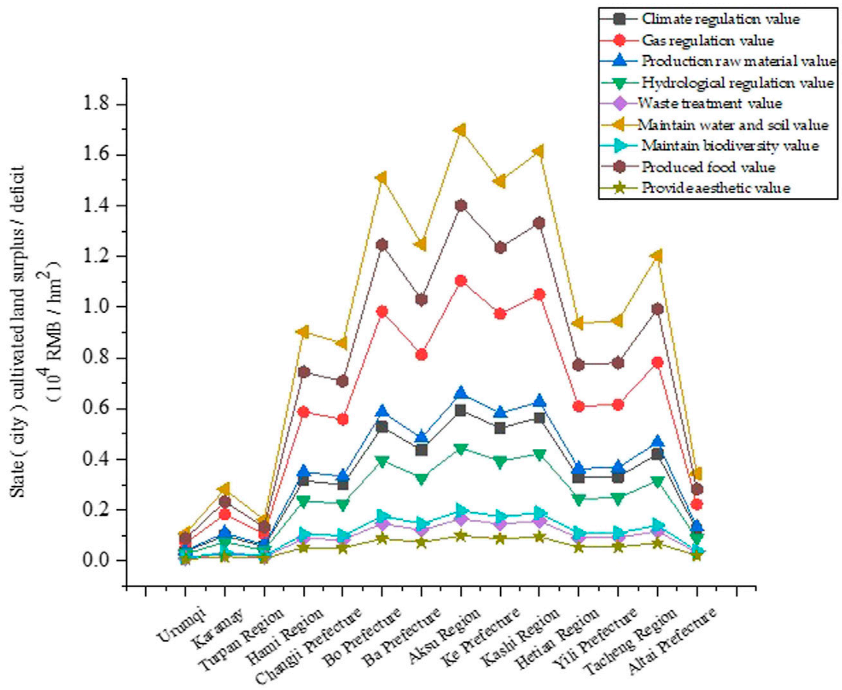

FIGURE 3
Positive ecological value of cultivated land in the state (city).

Academicians agree that the social security value and social stability value constitute the social value of cultivated land and that the social security value is reflected in the amount of social security that the cultivated land bears for farming households *in lieu* of government social security payments (Jin et al., 2018).

$$V_{sc} = V_L + V_y + V_j + V_{wd}. \tag{11}$$

1) Value of social old-age security for farmland

Assuming that the farmer loses his land and participates in the insurance with the average capital of an urban resident, the value of social pension insurance per unit area of the cultivated land is (Wang et al., 2008),

$$V_L = \left[(M \times m + W \times w) \times \frac{G_p}{G_o} \right] \Big/ s_r, \tag{12}$$

$$G_p = E + F = \frac{L_s + L_g}{2} \times T \times 1\% + \frac{v}{t}, \tag{13}$$

where V_L is the value of social pension protection for cultivated land; M and W are the bases of single contributions for male and female citizens; m and w are the proportions of male and female citizens in the total population; G_p is the basic pension, including basic pension E and individual account pension F; G_o is the monthly premium base; s_r is the area of cultivated land *per capita*; L_s and L_g are the average monthly wages of employed persons and indexed monthly wages of individuals in the previous year, respectively; T is the cumulative length of one's contributions; v is the cumulative storage capacity of individual accounts; and t is the number of months of accrual.

2) The value of medical insurance on farmland

Farmers' medical coverage is dependent on farmland, and farmers who lose their land should be entitled to compensation for medical insurance benefits (Yan et al., 2021). The calculation formula is

$$V_y = \frac{B}{R}, \tag{14}$$

where V_y is the value of the health insurance on the farmland; B is the annual health insurance contribution paid by the farmer per unit area; and R is the yield reduction rate.

3) Value of employment insurance on farmland

Farmers also need to be compensated for the value of employment security after losing their land. Referring to the unemployment security measures for urban residents, farmers are set to receive a minimum livelihood security payment from the time they lose their land until they retire (Zhu et al., 2011), calculated by the following formula:

$$V_j = [(c_m - c) \times m + (c_w - c) \times w] \times J \big/ s_r. \tag{15}$$

4) Social stability value of cultivated land

The social stability value is the value invested by the state to safeguard the productivity of cultivated land, mainly in the form

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TABLE 1 State (city)-cultivated land surplus/deficit.

Region	Total surplus (10^4 hm^2)	Area conversion factor	Standardization area (10^4 hm^2)
Urumqi	−63.94	0.27	−17.26
Karamay	−12.97	0.13	−1.69
Turpan region	−59.35	0.08	−4.75
Hami region	−6.71	0.28	−1.88
Changji Prefecture	55.01	0.62	34.11
Bo Prefecture	13.64	0.80	10.91
Ba Prefecture	6.56	0.34	2.23
Aksu region	32.39	0.66	21.38
Ke Prefecture	1.85	1.45	2.68
Kashi region	31.13	1.00	31.13
Hetian region	3.37	1.13	3.81
Yili Prefecture	61.06	1.13	69
Tacheng region	77.99	0.87	67.85
Altai Prefecture	22.08	0.31	6.84
Total	151.04	-	224.36

of cultivated land occupation tax a_1, cultivated land reclamation fee a_2, new vegetable land construction and development fund a_3, and new construction land paid use tax a_4 charged for occupying cultivated land (Zhu et al., 2011).

$$V_{wd} = a_1 + a_2 + a_3 + a_4. \tag{16}$$

3) Ecological value of cultivated land resources

Cultivated land ecosystems not only generate positive values, such as climate regulation, gas regulation, and production of raw materials (Cheng et al., 2019; Li et al., 2019), but also negative values, such as the excessive use of fertilizers and pesticides, and environmental pollution caused by residual mulch (Qi, 2013).

$$V_{eco} = V_{sz} + V_{sf}. \tag{17}$$

$$V_{sf} = v_{hn} + v_{dm}. \tag{18}$$

1) Positive value of ecological services of cropland

The dryland unit area equivalent factor refers to the results of the study by Xie et al. (2015), and the ratio of the cropland replanting index in the study area to the national cropland replanting index was selected as the biomass correction factor (Sun et al., 2007), which was calculated by the following formula:

$$V_{sz} = \frac{F_j}{F_0}\left[\left(\frac{1}{7} \times \sum_{i=1}^{n} \frac{p_i \times c_i}{C}\right) \times \gamma\right], \tag{19}$$

where V_{sz} is the positive value of the ecological services of cropland; F_0 and F_j are the cropland replanting indices of the country and study area j, respectively; C is the crop-sown area; and γ is the unit area equivalent factor.

2) Negative value of ecological services of the cultivated land

a. Negative value of environmental pollution caused by the excessive use of chemical fertilizer and pesticide in the cultivated land.

Due to the widespread use of pesticides and fertilizers by farmers, negative problems, such as eutrophication of water bodies, increased nitrate content in groundwater, and pesticide residues endangering human health, arise. The specific formula for its value is as follows (Liu et al., 2020):

$$v_{hn} = \left[h_f \times (1 - e_1) \times g_{h_f} + n_y \times (1 - e_2) \times g_{n_y}\right] / s, \tag{20}$$

where v_{hn} is the negative value of the cultivated land in the study area due to pesticides and fertilizers; h_f and n_y are the amount of fertilizers and pesticides used, respectively (Chen et al., 2002; Sun et al., 2007); e_1 and e_2 are the utilization rates of fertilizers and pesticides, respectively, with reference to the literature; 36% and 35% were taken in Xinjiang; and g_{h_f} and g_{n_y} are the prices of fertilizers and pesticides, respectively.

b. Negative value of mulch residues on cultivated land.

The negative value of residual mulch on cultivated land is calculated as follows, as it damages the soil structure, hinders soil water infiltration, and affects crop growth (Liu et al., 2020).

TABLE 2 Value of the cultivated land converted to construction land in the state (city) (10^4 RMB/hm^2).

Region	Proximity zone	Peri-urban area	Remote areas	Net gain from conversion of cultivated land to constructed land
Urumqi	1,375.00	770.00	536.67	699.79
Karamay	776.17	457.33	346.33	427.81
Turpan region	441.67	303.33	240.00	281.04
Hami region	326.67	222.33	143.00	185.79
Changji Prefecture	698.33	383.67	149.00	276.33
Bo Prefecture	365.00	250.67	151.00	202.67
Ba Prefecture	770.83	363.83	210.00	318.56
Aksu region	674.67	376.67	239.67	328.30
Ke Prefecture	349.00	250.67	102.30	157.75
Kashi region	533.67	423.67	234.33	319.08
Hetian region	409.33	215.83	180.00	217.62
Yili Prefecture	647.78	336.67	113.40	225.35
Tacheng region	426.83	225.00	124.00	187.10
Altai Prefecture	395.50	207.67	110.30	161.15
Total	-	-	-	284.88

$$v_{dm} = \left[d_m \times e_3 \times o \times \sum_{i=1}^{n} y_i \times c_i\right] \Big/ s, \tag{21}$$

where v_{dm} is the negative value caused by the residue of mulch on cultivated land; d_m is the area covered by mulch; e_3 and o are the ratio of the mulch residue and crop loss ratio—with reference to the literature study, 41.7% and 10% were taken in Xinjiang (Chen et al., 2002; Sun et al., 2007); and y_i is the yield of the ith crop.

2.3.4 Value-added benefits of converting cropland to construction land

Theoretically measured value-added benefits of converting cropland to construction land as a compensation standard is too idealistic and unrealistic, and the government's ability to pay should be considered as an important factor (Zhang and Zhang, 2021), so it needs to be revised. In addition, according to international practice, the maximum threshold for the development intensity of construction land in a city is 30%. Drawing on the ideas of Zhao and Liu (2013) and other urban development intensity measurements, the value should be revised. The formula for calculating the value-added benefit of converting actual cultivated land to construction land is

$$V'_f = V_{g\to J} - (V_{ec} + V_{sc} + V_{eco}), \tag{22}$$

$$V_f = (30\% - \varphi)\theta * V'_f, \tag{23}$$

$$\varphi = \frac{S_j}{S_z} \times 100\%, \tag{24}$$

$$\theta = \frac{\beta_1 - \beta_2}{\beta_3} \times 100\%. \tag{25}$$

V_f' is the theoretical value of the value-added benefit of converting cropland to construction land; V_f is the modified value-added benefit of converting cropland to construction land; φ is the current development intensity of the city; S_j and S_z are the total area of construction land and the whole region, respectively; θ is the government's ability to pay; β_1, β_2, and β_3 are the government's budget, final budget, and late payment for natural resources, respectively.

2.3.5 Calculation of value-added benefits from the conversion of cropland to constructed land

Whether compensation or payment of value-added benefits from the conversion of cropland to constructed land depends on the amount of cropland deficit in the study area is based on the actual value of development rights as measured by the following equation (Zhang et al., 2018):

$$V = Y \times V_f, \tag{26}$$

where V is the total given value of the right to develop cultivated land in the study area.

TABLE 3 Economic value of the cultivated land in the state (city).

Region	Total return on crop production (10^6 RMB)	Total cost of crop production (10^6 RMB)	A_1 net return per unit area (10^4 RMB/hm^2)	A total net return (10^4 RMB/hm^2)	Economic value of cultivated land (10^4 RMB/hm^2)
Urumqi	67.91	22.12	0.14	0.21	4.39
Karamay	158.76	278.73	−0.74	-0.68	−14.33
Turpan region	80.51	175.50	−0.17	−0.10	−2.14
Hami region	756.75	879.28	−0.17	−0.10	−2.12
Changji Prefecture	5,445.40	4,346.84	0.22	0.26	5.55
Bo Prefecture	2,470.77	2,671.46	0.00	0.07	1.48
Ba Prefecture	4,004.27	5,753.99	−0.45	−0.39	−8.20
Aksu region	9,477.69	13,311.47	−0.45	−0.39	−8.21
Ke Prefecture	739.76	408.70	0.44	0.47	9.98
Kashi region	9,784.65	12,236.70	−0.24	−0.19	−4.05
Hetian region	1,843.48	716.51	0.47	0.52	10.85
Yili Prefecture	5,754.17	1,352.35	0.85	0.85	17.91
Tacheng region	8,621.37	6,968.69	0.28	0.28	5.88
Altai Prefecture	869.63	195.82	0.26	0.30	6.38
Total	67,239.63	72,678.65	−0.01	0.07	1.37

3 Results

3.1 Determination of profit and loss of cultivated land

Based on the relationship between grain supply and demand, the surplus and deficit of cultivated land in the 14 states (cities) of Xinjiang were obtained according to Eq. 1 and relevant statistics (see Table 1).

The analysis concluded that the total supply of cultivated land in Xinjiang was greater than the total demand in 2018, which was consistent with the findings of related scholars (Yong and Zhang, 2012), with a total surplus area of 224.36 × 10^4 hm^2. In terms of state (city), the cultivated land in Urumqi, Karamay, Turpan, and Hami were deficit areas. Urumqi has the highest deficit, meaning that it needs to compensate for 17.26 × 10^4 hm^2 of cultivated land, and the second is Turpan, while Karamay and Hami had smaller deficits with 1.69 × 10^4 hm^2 and 1.88 × 10^4 hm^2, respectively. Due to the specificity of the climatic environment, these two areas are rich in melons and fruits, and the area under grain cultivation and the level of grain production are low. The remaining 10 cities and prefectures are in cultivated land surplus areas, which have more cultivated land and surplus cultivated land while meeting the demand, with the largest surplus being in Ili Prefecture directly under the city at 69.00 × 10^4 hm$^{'}$, followed by Tacheng Prefecture with a cultivated land surplus of 67.85 × 10^4 hm^2.

3.2 Net benefits of converting cropland to constructed land

As shown in Table 2, the realistic average net return from the conversion of cultivated land to construction land in Xinjiang in 2018 was 284.88 × 10^4/hm^2 RMB, of which the realistic value generated from the conversion of cultivated land to construction land in six regions, namely, Urumqi, Karamay, Aksu, Bayingguoleng Mongol Autonomous Prefecture, and Kashgar and Changji Hui Autonomous prefectures, was greater than the average value across Xinjiang. The better economic development and high benchmark land prices in these cities and prefectures have boosted the value of the cultivated land converted to construction land. The value of the cultivated land converted to construction land in the cities and counties directly under Ili Prefecture is close to the provincial average, and the benchmark land value is relatively high. The other seven regions have average

TABLE 4 Social value of the cultivated land in the state (city).

Region	Area cultivated land *per capita* (people/mu)	Value of old-age security (10^4 RMB/hm^2)	Value of medical insurance (10^4 RMB/hm^2)	Employment insurance value (10^4 RMB/hm^2)	Social value of cultivated land (10^4 RMB/hm^2)
Urumqi	0.50	10.43	232	57.5	309.18
Karamay	3.24	1.60	50.03	44.5	105.38
Turpan region	1.39	3.74	116.6	32.1	161.65
Hami region	2.69	1.93	60.26	29.46	100.90
Changji Prefecture	7.99	0.65	20.27	32.86	63.02
Bo Prefecture	5.88	0.88	27.52	24.5	62.15
Ba Prefecture	4.58	1.13	35.37	32.77	78.51
Aksu region	3.86	1.34	41.94	27.4	79.93
Ke Prefecture	1.73	2.62	81.75	18.75	112.37
Kashi region	2.30	2.26	70.45	29.3	111.26
Hetian region	1.34	3.87	120.6	22.5	156.23
Yili Prefecture	10.98	0.47	14.75	24	48.47
Tacheng region	34.21	0.15	4.733	26.4	40.53
Altai Prefecture	19.12	0.27	8.467	26	43.98
Total	-	-	-	-	105.25

economic development and low benchmark land prices, and the value of the cultivated land converted to construction land in these regions is much less than the average for the whole of Xinjiang.

3.3 Net return of cultivated land for agricultural development

(1)Calculation of the economic value of cultivated land

As shown in Table 3, the overall total return of cultivated land in Xinjiang in 2018 was greater than the total cost of the cultivated land, with the total net return reaching 0.07×10^4 RMB/hm^2 and the economic value of the cultivated land being 13,700/hm^2 RMB. In terms of crop returns and expenditures, wheat and cotton showed serious losses in net returns per unit area, with losses of 1,668.12 RMB/hm^2 and 18,355.2 RMB/hm^2, respectively. Only maize showed a better net return situation, and the overall economic benefits of the cultivated land were not significant. From the perspective of the state (city), the economic value of cultivated land in Urumqi, Changji Hui Autonomous Prefecture, Bortala Mongol Autonomous Prefecture, Kizilsu Kirgiz Autonomous Prefecture, Hotan Prefecture, Yili Prefecture, Tacheng Prefecture, and Altay Prefecture is positive. The main crops in these regions are wheat and maize, and the sowing area accounts for about 83.29% of the total sowing area on average. The economic value of the cultivated land in six states (cities) is less than 0. The possible reason is that the crops are mainly cotton, and the sowing proportion is 75.16%, resulting in the low economic value of the cultivated land.

(2) Measurement of the social value of cultivated land
   1) Calculation of the value of social old-age security for farmland

When calculating the basic pension, the average age of urban residents is 43 years as the average age of landless farming households. Referring to the China Life Insurance individual pension single payment cost, when citizens are insured at the age of 43, “M” and “W” are taken as 25,069 RMB and 24,965 RMB, respectively. The retirement age is set at 55 years, and the accumulated number of months

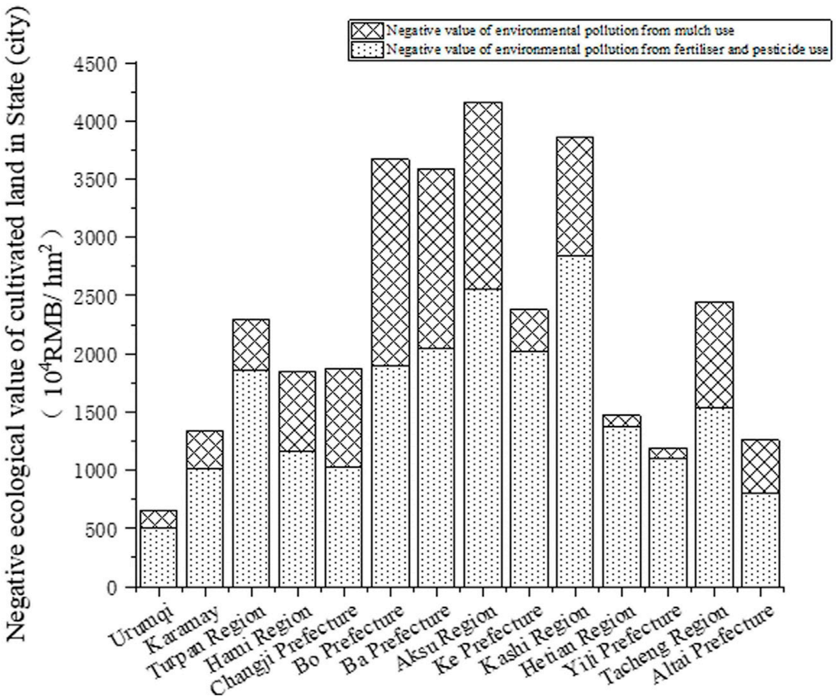

FIGURE 4
Negative ecological value of cultivated land in the state (city).

TABLE 5 Ecological value of cultivated land in state (city).

Region	Ecological value of cultivated land (10^4 RMB/hm^2)	Positive value is a multiple of the negative value (%)
Urumqi	0.34	6.12
Karamay	0.92	7.88
Turpan region	0.38	2.63
Hami region	3.20	18.32
Changji Prefecture	3.03	17.23
Bo Prefecture	5.29	15.42
Ba Prefecture	4.32	13.05
Aksu region	5.95	15.31
Ke Prefecture	5.37	23.62
Kashi region	5.67	15.70
Hetian region	3.36	23.84
Yili Prefecture	3.43	29.83
Tacheng region	4.26	18.45
Altai Prefecture	1.16	10.19
Total	3.33	-

TABLE 6 Correction factors for cultivated land compensation and measurement of actual value-added benefits in the state (city).

Region	Urban development intensity (%)	Government's ability to pay (%)	Ideal value-added benefit of converting cultivated land to constructed land (10^4 RMB/hm^2)	Actual value-added benefit of converting cultivated land to constructed land (10^4 RMB/hm^2)
Urumqi	6.49%	78.1%	385.88	70.86
Karamay	4.26%	75.4%	335.84	65.17
Turpan region	0.63%	70.0%	121.15	24.90
Hami region	0.43%	71.2%	83.81	17.65
Changji Prefecture	14.80%	72.0%	204.73	22.41
Bo Prefecture	0.95%	70.4%	133.75	27.35
Ba Prefecture	0.20%	73.6%	243.93	53.50
Aksu region	0.61%	74.2%	250.63	54.65
Ke Prefecture	0.10%	70.0%	30.03	6.29
Kashi region	0.62%	72.0%	206.20	43.62
Hetian region	0.10%	71.0%	47.18	10.01
Yili Prefecture	1.56%	72.3%	155.54	31.98
Tacheng region	0.78%	70.5%	136.43	28.10
Altai Prefecture	0.29%	70.3%	109.63	22.90
Total	-	-	174.63	34.24

of personal account pension payment is 170. Through Eqs 10, 11, the value of farmland social pension security is calculated.

2) Calculation of the value of farmland medical insurance

By checking the base of social insurance premium payment for flexibly employed persons released in Xinjiang in 2018, the base of medical insurance payment for flexibly employed persons is 352 RMB/month, and the reduction rate is taken as 4.57%. The value of medical insurance for cultivated land was calculated according to Eq. 12 to find the value of medical insurance for cultivated land.

3) Calculation of the value of farmland employment insurance

According to the minimum living security subsidy standard for urban and rural residents announced by the autonomous region, the minimum-security standard for urban areas in 2018 is 9,000 RMB per year. The retirement age of male and female citizens is 60 and 50 years, respectively, according to national regulations, and the average age in Xinjiang is 43 years. m and n are the approximate ratios of male and female citizens to the total population of 1:1. According to Eq. 13, the value of cultivated land employment insurance is obtained.

4) Calculation of the social stability value of cultivated land

According to "the cultivated land occupation tax law of the People's Republic of China," implemented in Xinjiang, combined with the actual situation of the autonomous region, to determine the cultivated land occupation tax within the autonomous region, and according to the "Circular on the Issuance of the Administrative Charge Standard for Land Management in the Autonomous Region System," the cultivated land reclamation fee shall be charged according to the cultivated land grade; according to the "Xinjiang new construction land paid use standard," a new construction land paid use tax is levied, according to urban land grade.

Summing up the aforementioned calculations, the social value was derived (see Table 4). From an overall perspective, the average social value of cultivated land in Xinjiang reached 105.25×10^4 RMB/hm^2 in 2018, of which the social security value accounted for 72.10% of the total social value, showing that cultivated land has a huge social security capacity for farming households. Looking at the state (city), the seven regions of Urumqi, Turpan, Karamay, Kashgar, Hetian, Hami, and the county-level administrative regions under the autonomous

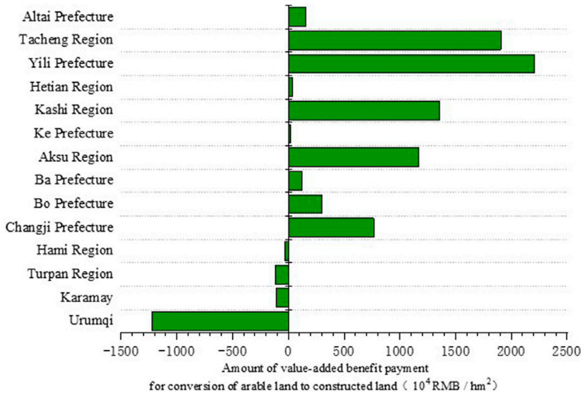

FIGURE 5
Distribution of value-added benefit payments for conversion of cultivated land to constructed land in the state (city).

region are all greater than the average across Xinjiang, with the social value of cultivated land in Urumqi being the highest at 309.18 × 10^4 RMB/hm^2, followed by Turpan with a social value of 161.68 × 10^4 RMB/hm^2; both of these places show high average monthly salary of employees, but the *per capita* cultivated land is very low, at 0.03 person/hm^2 and 0.09 person/hm^2, respectively, and the cultivated land is under greater pressure to protect and enhance the social security value; the lowest social value of cultivated land is in Altai, at 40.52 × 10^4 RMB/hm^2, with a lower salary of 4,085.25 RMB for employees on the job, but its *per capita* cultivated land is higher at 2.28 person/hm^2.

(3) Calculation of the ecological value of cultivated land

1) Positive ecological value of cultivated land

As shown in Figure 2, the average amount of the positive ecological value of cultivated land in Xinjiang in 2018 was 6.13 × 10^4 RMB/hm^2, of which the value produced by the function of maintaining soil and water and producing food in cultivated land were higher, at 1.64 × 10^4 RMB/hm^2 and 1.35 × 10^4 RMB/hm^2, respectively. Looking at the state (city) (see Figure 3), the positive ecological value of cultivated land in Aksu, Kashgar, Bozhou, Kizilsu, Bazhou, and Tacheng is higher than the provincial average, 6.36 × 10^4 RMB/hm^2, 6.05 × 10^4 RMB/hm^2, 5.66 × 10^4 RMB/hm^2, 5.61 × 10^4 RMB/hm^2, 4.68 × 10^4 RMB/hm^2, and 4.51 × 10^4 RMB/hm^2, respectively. The positive ecological value is mainly related to the biomass in the regional ecosystem. The aforementioned regions have a large area of crops, and the total crop yield is far beyond the provincial average, resulting in a greater ecological value. Ili Prefecture is close to the provincial average and the area of the crop-planting land is also higher, but the planting structure is different and the area is dominated by wheat and corn. The positive ecological value of cultivated land in Urumqi and Turpan is low, mainly due to the small area of crop planting. The former is mainly wheat, and the latter is mainly cotton.

2) Negative ecological value of cultivated land

Pesticide use in the prefecture (city) is difficult to obtain. With the help of the research idea of Huang et al. (2019), the high positive correlation between pesticide use and crop yield is obtained by multiplying the crop share by the total pesticide use in the whole territory. The prices of fertilizers and pesticides were 6.33 RMB/hm^2 and 116.70 RMB/hm^2, respectively. By substituting the overall obtained data into Eqs 17, 18, the negative value of the excessive use of fertilizers and pesticides on cultivated land and the environmental pollution caused by the residue of mulch on cultivated land in Xinjiang State (city) in 2018 can be derived (see Figure 4). The analysis concluded that the negative ecological value of mulch pollution was high, with the highest negative ecological value in the autonomous county-level administrative regions.

Summing up the calculations, the total ecological value of cultivated land all over Xinjiang State (city) was derived (see Table 5), and as a whole, the average ecological value across Xinjiang in 2018 was at 3.33 × 10^4 RMB/hm^2, which was closely related to the increase in crop yield and value. Among the 14 states (cities), the positive ecological value of the cultivated land was much greater than the negative ecological value, with the highest multiple being 29.83 in Ili Prefecture. The largest ecological value of the cultivated land is of Aksu, with the value being 5.94 × 10^4 RMB/hm^2.

3.4 Calculation of the value-added benefit of converting farmland to construction land

The aforementioned calculation results were combined to obtain the ideal value-added benefit of converting farmland to

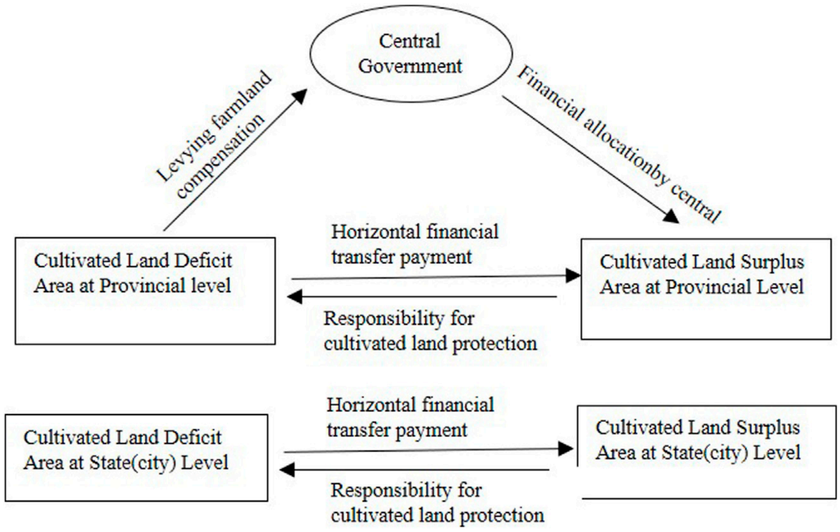

FIGURE 6
Establishing a compensation method combining various forms.

construction land. Based on the urban development intensity and the government's ability to pay correction factor, the final value-added benefit of converting cultivated land to construction land in an average state is 34.24×10^4 RMB/hm^2 (see Table 6). Among them, Urumqi, Karamay, Bazhou, Aksu, and Kashgar exceed the average level of the whole Xinjiang area, the benchmark land prices in these regions are higher, the government's ability to pay is also higher, and the value of real cultivated land converted to construction land is also increased; the value-added benefits of cultivated land converted to construction land in the two regions of Tacheng and Yili are close to the average level of Xinjiang, the benchmark land price is above the middle level, the potential development intensity of the city is large, and the compensation standard of cultivated land protection is improved. Changji city's potential development degree is the smallest, reducing the value; in other regions, the benchmark land price is low, and the social value of the cultivated land is high. Even if the potential development intensity is high, it cannot improve the compensation standard of cultivated land protection.

3.5 Cultivated land protection compensation payment amount

According to the profit and loss situation of the cultivated land in the 14 states (cities) of Xinjiang, and the actual value of the value-added benefit of cultivated land converted into construction land, the amount of compensation for regional cultivated land protection can be obtained by Eq. 22 (see Figure 5). The analysis shows that the value-added benefits of Urumqi, Karamay, Turpan, and Hami are negative, and they need to pay $1,223.04 \times 10^4$ RMB, 110.14×10^4 RMB, 118.28×10^4 RMB, and 33.18×10^4 RMB for cultivated land protection compensation. The most serious loss in Urumqi is mainly due to the rapid development of non-agricultural industries in this area; the demand for cultivated land is more, the deficit of cultivated land is large, and the *per capita* cultivated land is the lowest in the province, so the payment amount reaches the highest. In the other 10 cities, the value-added benefits of cultivated land converted into construction land are relatively surplus. Among them, Yili Prefecture has the highest compensation amount of $2,206.62 \times 10^4$ RMB due to the abundant cultivated land area in Ili Prefecture, the largest amount of grain surplus, and the responsibility of protecting cultivated land.

4 Conclusion

1) Xinjiang's cultivated land resources were in a surplus state, and the total surplus area was 224.36×10^4 hm^2. From the perspective of prefectures and cities, there are four deficit areas, Urumqi, Karamay, Hami, and Turpan. Among them, Urumqi has the most serious loss, which is 17.26×10^4 hm^2, and its 10 cultivated land resources are surplus areas.
2) The compensation standard for cultivated land protection in Xinjiang in 2018 was 34.24×10^4 RMB/hm^2. The compensation standards of cultivated land protection in each state (city) are mainly affected by the benchmark land price and the three values of cultivated land. Among them, the benchmark land price is the core factor affecting value-added benefits. Among the three values of cultivated land, the calculation results of the economic value of cultivated land in each city are quite different, and the ecological value also has certain differences. The social

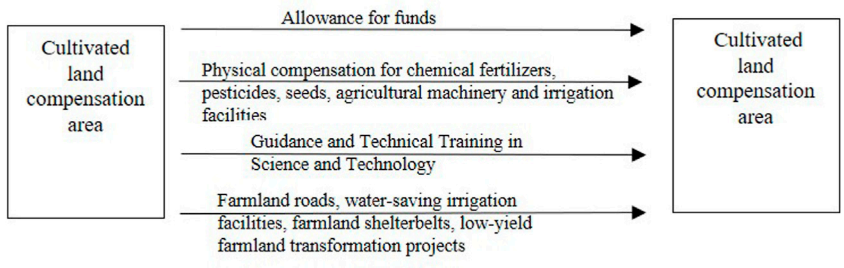

FIGURE 7
Double-horizontal financial compensation.

value of cultivated land with large differences affects the value-added benefits of prefectures and cities to some extent.

3) The overall compensation for cultivated land protection in Xinjiang was large, up to 7,682.57 × 10^4 RMB. From the level of cities and states, Urumqi, Karamay, Turpan, and Hami are in areas that pay compensation for cultivated land protection, while Tacheng, Yili, Changji, Kashgar, Bozhou, Altay, Bazhou, Hotan, and Kezhou are in areas that receive compensation for cultivated land protection.

5 Discussion

Based on the value-added benefit model of converting cultivated land to construction land, this study combined the profit and loss of cultivated land to measure the standard of compensation for cultivated land protection, which to a certain extent plays a positive role in the protection of cultivated land resources and the coordinated economic and social development between regions. Comparing the calculation results of this paper with existing studies, Wen et al. (2021) measured the value of cultivated land development rights in various provinces across China by constructing an analytical framework for cultivated land protection compensation, which was 42.44 × 10^4 RMB/hm^2 in Xinjiang. Zhang et al. (2018) calculated the value of arable land development rights in Shaanxi Province in 2016 as 50.57 × 10^4 RMB/hm^2. Zhu (2020) measured the value of development rights in Henan Province in 2017 as 25.78 × 10^4 RMB/hm^2. This study and the aforementioned studies both draw on the theory of the development rights value of cropland and then measure the compensation value of cropland protection. Due to the differences in land values and statistical data caused by the differences in research time points and research fields, the results of this study are somewhat different from those of the other studies, but there are similarities in the ideas of constructing the compensation measurement model for cropland, and it is consistent with the actual situation, which indicates the rationality and scientificity of the compensation measurement model constructed in this study. With a more in-depth comparison, this study fully considers the real situation and invokes two correction factors, namely, the government's ability to pay and the urban development potential, to correct the value of compensation, while other studies only consider the intensity of urban development, but the government's ability to pay is not explored, and when measuring the value of the cultivated land itself, the measurement of the economic value of cultivated land and the ecological value of cultivated land are added to improve the measurement system. However, the measurement of compensation rates for cultivated land protection is only the basic work of the compensation mechanism for arable land protection, and it is necessary to establish supporting facilities to ensure the realization of a farmland protection compensation mechanism (see Figure 6).

(1) Establishing a compensation method combining various forms

The realization of compensation and payment for cultivated land protection needs strong economic support. However, the overall economic development strength of Xinjiang Province is weak, and the economic development levels of cities and prefectures in the province are also significantly different. It is not suitable to use all the methods of financial subsidies, and hence, a variety of methods, such as capital compensation, material compensation, technical services, and project compensation, should be used.

1) Financial compensation is the most urgently needed compensation. The compensation area compensates part of the fund for the compensation area, that is, the economic compensation fund for cultivated land protection raised from the cultivated land deficit area and social donations, and directly returns it to the local governments and farmers in the cultivated land surplus area in the form of currency according to the corresponding compensation standard, which can effectively realize the fairness of the utilization of the ecological and social benefits of cultivated land; promote the

coordinated development between regions; and at the same time, help ensure food security, ecological security, and the stability of the enjoyment of the ecological and social benefits of cultivated land.

2) Physical compensation. The compensation area provides chemical fertilizers, pesticides, seeds, agricultural machinery, and farmland water conservancy facilities in the compensation area, such as the construction of water conservancy and many other types of physical compensation methods, which can effectively avoid the "abuse" of compensation funds. While meeting the needs of some of the life and means of production of the farmers who are the most direct subjects of cultivated land protection, it also reduces the agricultural investment costs of cultivated land users and operators in the key areas of cultivated land protection and improves the economic benefits of farmers, which also plays a certain role in improving the living environment and living standards.

3) Technical services. The compensation area provides technical services to the compensation area, that is, to provide scientific and technological guidance and training to the responsible subjects for implementing farmland protection. This method is conducive to the popularization of advanced farming techniques and cutting-edge farming concepts and is also the key to improving the production capacity of cultivated land. Specific compensation methods include developing pollution-free pesticides, fertilizers, and other production factors, creating new agricultural tools, providing technical compensation advice and guidance to strengthen straw stubble returning technology, residual film recovery, water-saving irrigation technology, and transporting agricultural management and technical personnel to help improve food production and increase farmers' income in major grain-producing areas.

4) Project compensation. It is suggested to strengthen the project promotion of farmland roads, water-saving irrigation facilities, farmland shelterbelts, and the transformation of medium- and low-yield fields in some compensated areas. It is suggested to adopt open tender procurement and strengthen the supervision of the use of compensation funds for village collective organizations.

(2) Multi-channel financing to increase sources of compensation funds

With the source of compensation at the provincial level, in addition to the subsidy funds allocated by the central government, Xinjiang as a whole is a surplus area of cultivated land throughout the country and bears part of the responsibility for protecting cultivated land in the province with a deficit in the cultivated land. The state can levy a compensation tax on the cultivated land in the province with a deficit in cultivated land, establish a fund management committee to be responsible for the collected tax, and then subsidize the surplus area of cultivated land according to the surplus area of each province.

The compensation funds in the province should be guided by the provincial level and supported by the cities and counties to create a comprehensive and three-dimensional fund pool. In terms of the source of compensation, it is paid by the compensation area according to certain compensation standards and incorporated into the farmland protection institutions. Through the financial transfer payment, it is specially used for the benefit compensation of the compensation area. At the same time, relevant policies can be introduced to encourage and guide social capital investment and ensure the stable source of funds. In addition, the surplus cultivated land index can also be sold to the deficit area where the cultivated land resources are scarce, and the task of the balance of cultivated land occupation and compensation cannot be completed, which is not only conducive to the division of labor and cooperation between regions but also promotes the coordinated development of economic development and cultivated land protection. It also helps curb the phenomenon of over-occupation of cultivated land in areas that cannot complete the occupation of cultivated land and ultimately achieve the purpose of protecting cultivated land (see Figure 7).

(3) Establishing a dynamic accounting platform and supervisory and management institutions for compensation standards for cultivated land protection, and forming a long-term mechanism for compensation for cultivated land protection

In determining the compensation standard for cultivated land, it is necessary to take into account the constant changes in the urban benchmark land price and the three values of cultivated land. A dynamic accounting platform needs to be established to effectively improve the accuracy of the calculation of the value-added benefits of converting cultivated land into construction land so as to ensure the long-term feasibility of the compensation standard for the protection of cultivated land. In addition to the establishment of a protection and supervision and management agency for cultivated land protection compensation, the compensation for cultivated land protection will be paid by the cultivated land deficit areas to the cultivated land compensation protection agency in accordance with the compensation standards and will be paid by the protection agency to the cultivated land surplus areas through financial allocations as compensation for farmers' benefits. On the basis of good supervision of the funds, the scope and channels for the use of the funds are further broadened, and certain discretion is given to the units responsible for the protection of cultivated land so as to avoid the grassroots being tied up in the use of compensation incentive funds, resulting in a large surplus of funds that do not play their proper role. The "balance point" between fund supervision and fund use can be improved through the management measure of "spending money to ask for results and being accountable for ineffectiveness."

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

YW and XY conducted the analysis and wrote the manuscript. XY provided data and paper corrections. GY provided thesis data and editing. ZF edited the manuscript. BX offered suggestions for revision. LW corrected the manuscript.

Funding

This study was supported by the Special Project for Innovation Development of Shihezi University (Project No. CXFZSK202105 and CXFZ202217), the Science and Technology Research Project in Key Areas of the Corps (Project No. 2021AB021), the Program for Youth Innovation and Cultivation of Talents of Shihezi University (Project No. CXPY202223), and the Program for Young Innovative Talents of Shihezi University (Project No. KX00300302).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 04 January 2023
DOI 10.3389/fenvs.2022.1097236

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Land Use Dynamics, a section of the journal Frontiers in Environmental Science

RECEIVED 13 November 2022
ACCEPTED 05 December 2022
PUBLISHED 04 January 2023

CITATION
Hu Q, Gao X, Wang S, Wang Q, Qin Y, Zhang W, Lun F and Li Z (2023), Exploring the characteristics and driving forces of orchard expansion in ecological fragile region: A case study of three typical counties in the Loess Plateau.
Front. Environ. Sci. 10:1097236.
doi: 10.3389/fenvs.2022.1097236

Exploring the characteristics and driving forces of orchard expansion in ecological fragile region: A case study of three typical counties in the Loess Plateau

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The Loess Plateau exemplifies the type of ecologically fragile region that faces severe poverty challenges in China. Orchards have expanded rapidly over the past few decades and now constitute a considerable part of local economy. Not only do the characteristics of orchard expansion affect local economic development, but also exert additional pressure on the ecological environment. Therefore, it is essential for sustainable development on the Loess Plateau to investigate the characteristics and driving forces of orchard expansion. The Fuxian, Luochuan, Huangling, three typical orchard planting counties were chosen as the study area. Firstly, the orchard was extracted from the land use/cover classification from 1990–2020. It broadens the research approach to the identification of expansion cash crops by using the combination of linear spectral mixture analysis (LSMA) and decision tree. Secondly, the spatiotemporal dynamics of orchard expansion were quantitatively investigated based on spatial geometry center shift, physical geographical features, landscape pattern and orchard planting suitability. Then, we constructed an evaluation indicators system to detect the feature importance and partial dependence of different factors by random forest regression. It is more innovative to employ the machine learning method to investigate driving forces. Finally, the linkages between planting suitability and orchard expansion were further discussed, and subsequent policies were proposed. Findings demonstrated the orchard had continuously expanded over the past 30 years, with the fastest expansion rate during 1990–2005. Increased cohesion was accompanied by a shift in the orchard's spatial distribution to the north central region and highly suitable planting regions. Slope turned out to be the primary factor affecting the orchard expansion. In the future, regions with aging orchard but high planting suitability should be the preferred choice for orchard expansion. Additionally, the transportation connectivity and governmental assistance are crucial considerations for the future planning of the orchard.

KEYWORDS

orchard expansion, driving forces, ecological fragile region, linear spectral mixture analysis, Loess Plateau

1 Introduction

The Loess plateau (LP) is a globally well-recognized ecological fragile region (Fu et al., 2017; Fu, 2022), with severe social-ecological issues, including soil erosion (Zhou et al., 2016; Lu et al., 2022), water shortage (Feng et al., 2016) and poverty (Patrick, 2016). The conflict between socioeconomic development and environmental protection is a crucial challenge that needs urgent solutions. Orchard planting is characterized by high economic benefits and now serves as the backbone of the local economy in the LP (Chen et al., 2021). In addition, with the improvement of the dietary structure (Guo et al., 2022), the LP, one of the largest apple planting regions, has gone through significant orchard expansion in recent decades (Yang et al., 2020). Thus, the spatiotemporal dynamics of agricultural land will not only affect the local socio-economy, but also on its ecological condition.

Previous researches on agricultural land in the LP has focused on its economic benefits and associated environmental effects along with the land use/cover change (Zhao et al., 2018; Liang et al., 2018; Li et al., 2021; Huo et al., 2022; Xiao et al., 2022). There are many excellent reviews promoting sustainable agricultural land management in the LP, which also provide valuable instruction for socioeconomic development. However, the existing studies paid much attention to traditional food crops (Tracy, 2020; Wang et al., 2022a; Wang et al., 2022b; Chen et al., 2022; Wu et al., 2022; Wang and Cheng, 2022), while cash crops still remained unclear. Consequently, it is necessary to explore the spatiotemporal dynamics of orchard expansion and its driving forces in order to propose optimizing strategies for orchard planting in the LP.

Much work so far in terms of orchard expansion can be divided into three aspects: 1) identification of orchard expansions (Dong et al., 2013; Jason et al., 2017; Sun et al., 2017; Kaspar and Jefferson, 2018; Lin et al., 2022). Depending on multiple spectral indices and phenological information, much attention has been paid to identifying the expansion of different orchards. Zhu et al. (2020) extracted apple orchards in Qixia county from 2000–2017 by using normalized difference vegetation index (NDVI) time series and phenological vegetation information. Xuan et al. (2018) applied the random forest method to extract citrus orchards by using NDVI, soil-adjusted vegetation index (SAVI) and normalized difference moisture index (NDMI). Based on the phenological difference. The selection of the appropriate spectral indices and the extraction of the corresponding phenological information is a major challenge for different regions and different fruit tree species; 2) analysis on the characteristics of orchard expansion, including landscape pattern (Guzmán et al., 2022), dynamics (Dibs et al., 2017; Peña-Cortés et al., 2021) and planting suitability (Wu et al., 2022). As for analyzing the characteristics of orchard expansion, current studies are based on a single perspective. Naqash and Wani. (2019) discovered the spatiotemporal dynamics of orchard expansion in Kashmir Valley and proposed policy suggestions from the perspective of pest control. Guzmán et al. (2022) analyzed the landscape pattern of olive orchards expansion in Spain. A comprehensive investigation of the spatiotemporal dynamics of orchard expansion based on multiple perspectives is still lacking; 3) driving mechanism of orchard expansion (Xiao et al., 2015; Zhang et al., 2017). Driving force analysis based on statistical regression models (e.g., logistic regression model) is a common method for analyzing the driving mechanisms of orchard expansion. Although abundant potential determinants have been selected to figure out the driving mechanism, the underlying response mechanism is not further used to suggest new policy actions. More effort is needed to determine how to provide sustainable orchard management practices based on the understanding of the driving forces.

In general, scholars have made certain achievements in the study of orchard expansion. However, the comprehensive exploration of orchard expansion dynamics in the ecological fragile region and their driving forces are still lacking. Northern Shaanxi is one of the most vital regions for orchard cultivation in the LP. Therefore, this study takes the three typical apple orchard planting counties as the study area. The spatiotemporal dynamics of orchard expansion have been analyzed from the perspectives of spatial geometry center shift, physical geographical features, landscape pattern and orchard planting suitability. It broadens the research approach to the identification of expansion cash crops in ecologically vulnerable areas. Furthermore, it is more innovative to employ the machine learning method to investigate driving forces and put forward matching policies in order to promote the apple industry in the LP.

The specific objectives of this study are: 1) to map the land use/cover classification of the study area and identify orchard expansion from 1990 to 2020; 2) to analyze the spatiotemporal dynamics of orchard expansion based on the spatial geometry center shift, physical geographical features, landscape pattern and orchard planting suitability; 3) to reveal the potential determinants and analyze its driving forces based on the parameter of feature importance and partial dependence; 4) to propose optimistic strategies for local orchard expansion based on above findings for better agricultural land management and ecological conservation.

2 Materials and methods

2.1 Overall workflow

Figure 1 shows the overall workflow of this study. The whole research is carried out in two steps. Firstly, based on the three

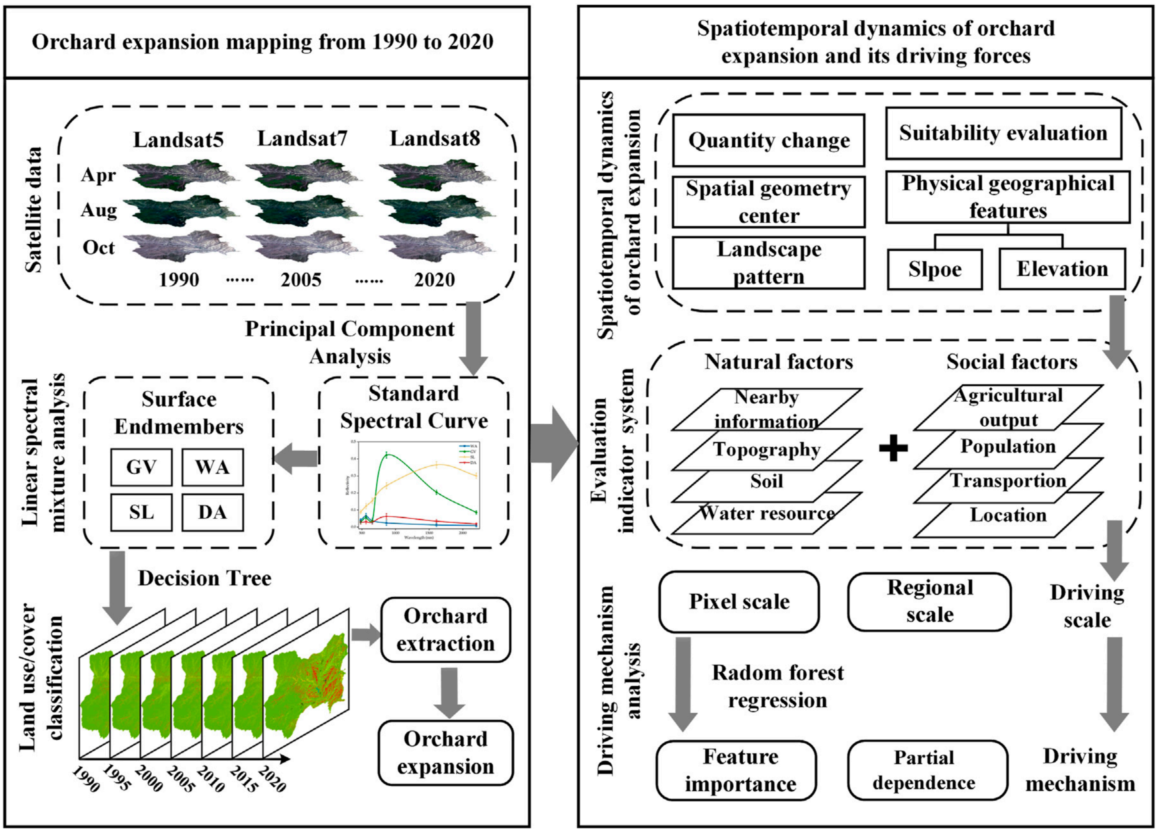

FIGURE 1
Overall workflow of the research.

temporal remote sensing data, the land use/cover classification of the study area from 1990 to 2020 was obtained by using a combination of the LSMA and the decision tree. The spatial distribution of orchard expansion was then available by extracting the orchards. Secondly, the spatiotemporal dynamics of orchard expansion were investigated from the perspectives of spatial geometry center shift, physical geographic features, landscape pattern and planting suitability. Combined with the constructed evaluation system of influencing factors, the feature importance and partial dependence of different factors were analyzed by using random forest regression.

2.2 Study area

The counties of Fuxian, Luochuan and Huangling in Yan'an City, Shaanxi Province were selected as the study area (Figure 2). The three counties are situated between 108°29′–109°42′N and 35°44′–36°23′E, covering an area of 8,278 km^2. These counties are located in the middle part of the LP, where the ecological environment is fragile and soil erosion is serious. This area belongs to the temperate continental monsoon climate, with sufficient sunlight and pleasant weather. The terrain in the study area is complex, including river valley terrace, low hills and loess valleys. The local government attaches great importance to the investment and policy support of the apple industry, guiding the farmers and promoting the fruit industry. At present, this area has become one of the largest apple production areas in China, of which Luochuan county's apple yields rank the first, known as the "apple capital".

2.3 Data source

2.3.1 Satellite data

In this study, the surface reflectance data from Landsat TM/ETM +/OLI C2L2 products with radiometric calibration, geometric correction, and atmospheric correction were used. The Landsat satellite images have a 16-day return time and 30 m spatial resolution, which are available from 1972 to the present (Roy et al., 2014) and have been widely used in land use/cover classification (Azzari and Lobell, 2017; Jin et al., 2019;

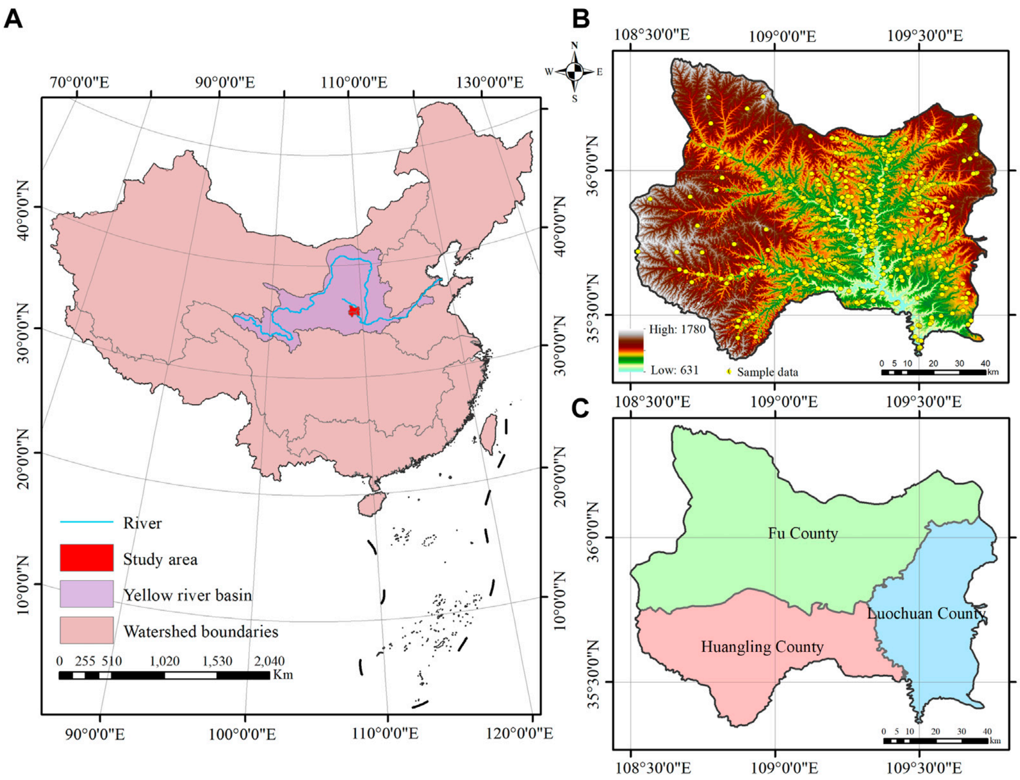

FIGURE 2
Study area and its associated information. **(A)** Location of the study area in the Losses Plateau; **(B)** Topography of the study area and samples on the field; **(C)** The three typical counties in the study area.

Souza et al., 2020). All images are freely available on the website of the United States Geological Survey (https://earthexplorer.usgs.gov). In this study, the "landsat_gapfll.sav" plug in of ENVI version 5.3 software (Exelis Visual Information Solutions, Inc., Boulder, CO, United States) was used to compensate for the loss of ETM + data. The cloud coverage of the images used in this study was less than 8%, and the cloud areas were not in the study area. Thus, no additional cloud removal processing was required.

In the study area, the periods of significant physical characteristics of the orchards include: 1) growth period (April-May): the period when fruit trees start to sprout and grow leaves; 2) peak period (August-September): the period when fruit trees have the largest green leaf area; 3) deciduous period (October-November): the period when most deciduous forests have turned yellow and deciduous, while fruit trees are still covered with green leaves without significant deciduousness. To distinguish different land types in the study area, Landsat satellite images for April, August and October of 1990, 1995, 2000, 2005, 2010, 2015, and 2020 were used in this study, among which Landsat5 TM images were used for 1990, 1995, 2005, and 2010, Landsat7 ETM+ images were used for 2000, and Landsat8 OLI images were used for 2015 and 2020. The images used in this study are shown in Table 1.

2.3.2 Field data

To obtain reference samples for decision tree construction and validation samples for land use/cover classification, we collected field data in July 2021, using a portable GPS satellite positioning navigator to collect the geographic coordinates and the land use/cover type. In addition, we selected sample sites for different land use/cover types that have not changed between 1990 and 2020 based on visual interpretation of high-resolution historical images from Google Earth. In the study area, we selected 758 sample points of various types, including 167 orchards, 162 cultivated land, 197 forest land, 47 grassland, 119 water, 18 bare land, and 48 construction land (Figure 1B).

2.4 Orchard expanding mapping

2.4.1 Linear spectral mixture analysis

The theoretical assumption of the LSMA is that the radiant brightness of the ground target pixel received by the sensor is only related to the proportion of the area occupied by each element (Li et al., 2021). Therefore, the reflectance of the ground target pixel is a linear combination of each endmember

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TABLE 1 Details of satellite data used in this study.

Year	Satellite	Product	Date	Cloud coverage (%)
2020	Landsat8	OLI TIRS C2T2	4/25	0
			8/2	0
			9/30	5
2015	Landsat8	OLI TIRS C2T2	4/28	0
			8/15	1
			10/2	0
2010	Landsat5	TM C2L2	4/30	0
			6/30	0
			10/7	0
2005	Landsat5	TM C2L2	4/19	0
			9/10	0
			10/9	8
2000	Landsat7	ETM C2L2	5/12	0
			9/17	0
			9/23	0
1995	Landsat5	TM C2L2	4/23	0
			8/13	0
			9/22	2
1990	Landsat5	TM C2L2	4/7	0
			8/29	0
			10/8	6

reflectance within the pixel, with the proportion of the area occupied by each endmember as a weight (Small, 2003). In the unit pixel, endmember abundance values (EMA) are calculated by the area percentage of each standard endmember at the subpixel level based on the pixel spectrum. The EMA with specific physical meaning, in contrast to other traditional vegetation indices, such as NDVI, NDMI and SAVI, can better reflect the information of landscape features (such as plants, soil, water, and so on) (Li et al., 2021). The selection of appropriate spectral indices is a major challenge for different regions when conducting land use/cover mapping. Thus, using the LSMA to convert raw spectral data from remote sensing images into physically meaningful EMA is beneficial to land use/cover classification.

Before the LSMA, there are two critical steps: principal component analysis (PCA) and endmember selection. Firstly, we used the PCA method to extract the main feature information of spectral space. Taking the PCA method results in 2020 as an example, the cumulative contribution of the top three principal components in three seasonal images exceeded 98% (Table 2), showing that the top three principal components of all images contained nearly all the spectral information. Consequently, we can determine that the intrinsic dimension of spectral information is three. According to the convex geometry theory, the number of endmembers is generally one more than the intrinsic dimension of the spectral space (Boardman, 1993). Therefore, we can select four pure spectral endmembers in the study area. Secondly, we built scatter grams based on the top three principal components to select pure endmembers. According to the spectral curve of points at the top of the scatter grams and the true color composite images, we determined four endmembers in the study area: soil (SL, rock and soil), green vegetation (GV, green photosynthetic leaves), dark (DA, shadow of mountains and vegetation) and water (WA).

There will be slight differences when extracting the endmember spectrum from the images of different satellite sensors (Han et al., 2022). To limit the influence of different sensors on the LSMA, we used the average values of six common bands (blue, green, red, near-infrared, and

TABLE 2 Principal component analysis of the top three principal components in 2020.

Image time	Principal component	Contribution rate (%)	Cumulative contribution rate (%)	Eigenvalue					
				Blue	Green	Red	NIR	SWIR1	SWIR2
2020-04	PC1	78.15	78.15	0.20	0.25	0.42	0.14	0.53	0.62
	PC2	19.32	97.47	0.06	−0.05	0.12	−0.97	−0.06	0.18
	PC3	2.03	99.50	−0.20	−0.37	−0.57	−0.10	0.68	0.07
2020-08	PC1	60.64	60.64	−0.12	−0.20	−0.23	−0.67	−0.53	−0.38
	PC2	36.32	95.96	0.17	0.21	0.38	−0.70	0.24	0.48
	PC3	2.84	98.80	0.25	0.37	0.55	0.21	−0.64	−0.11
2020-10	PC1	89.90	89.90	0.11	0.18	0.24	0.49	0.65	0.49
	PC2	6.63	96.53	0.02	−0.06	0.00	−0.85	0.34	0.41
	PC3	2.75	99.28	−0.34	−0.48	−0.60	0.13	0.45	−0.14

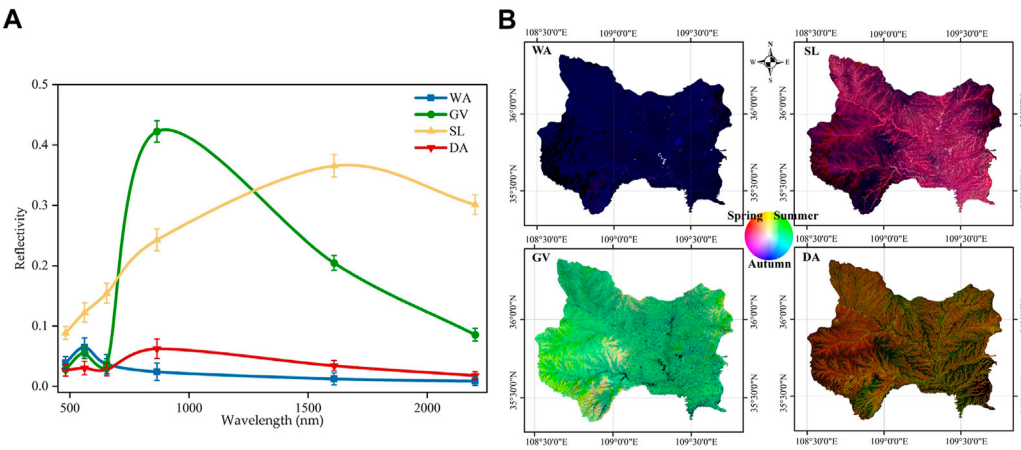

FIGURE 3
The standard spectral curves and fractional abundance of four endmembers. **(A)** The four endmembers include soil (SL, rock and soil), green vegetation (GV, green photosynthetic leaves), dark (DA, shadow of mountains and vegetation) and water (WA); **(B)** three-temporal false color composite images, where red, green, and blue represent endmember fractional abundance in spring, summer and autumn, repetitively.

shortwave-infrared 1/2) from three data sources to construct a standard endmember library (Figure 3A). These endmember spectra have been proven to be effective and stable (Sun and Liu, 2015; Sun et al., 2019). Finally, we estimate the EMA through the LSMA. The EMA results in 2020 are shown in Figure 3B.

2.4.2 Decision tree

In this study, the land use/cover types were selected into seven categories: Orchard, forest, grassland, water, cultivated land, construction land, and bare land. And we utilized the decision tree classification for land use/cover classification. Decision tree is a well-recognized classification method that does not need complex data processing and simply requires categorization based on the classification criteria and specific features (Mahesh and Paul, 2003; Thoreau et al., 2009). The decision tree was built by the LSMA results, ground features, and the phenological information of different crops. The segmentation threshold was determined by repeated experiments based on the histogram of the training samples' EMA. The decision tree is shown in Figure 4. And the specific classification rules are as follows:

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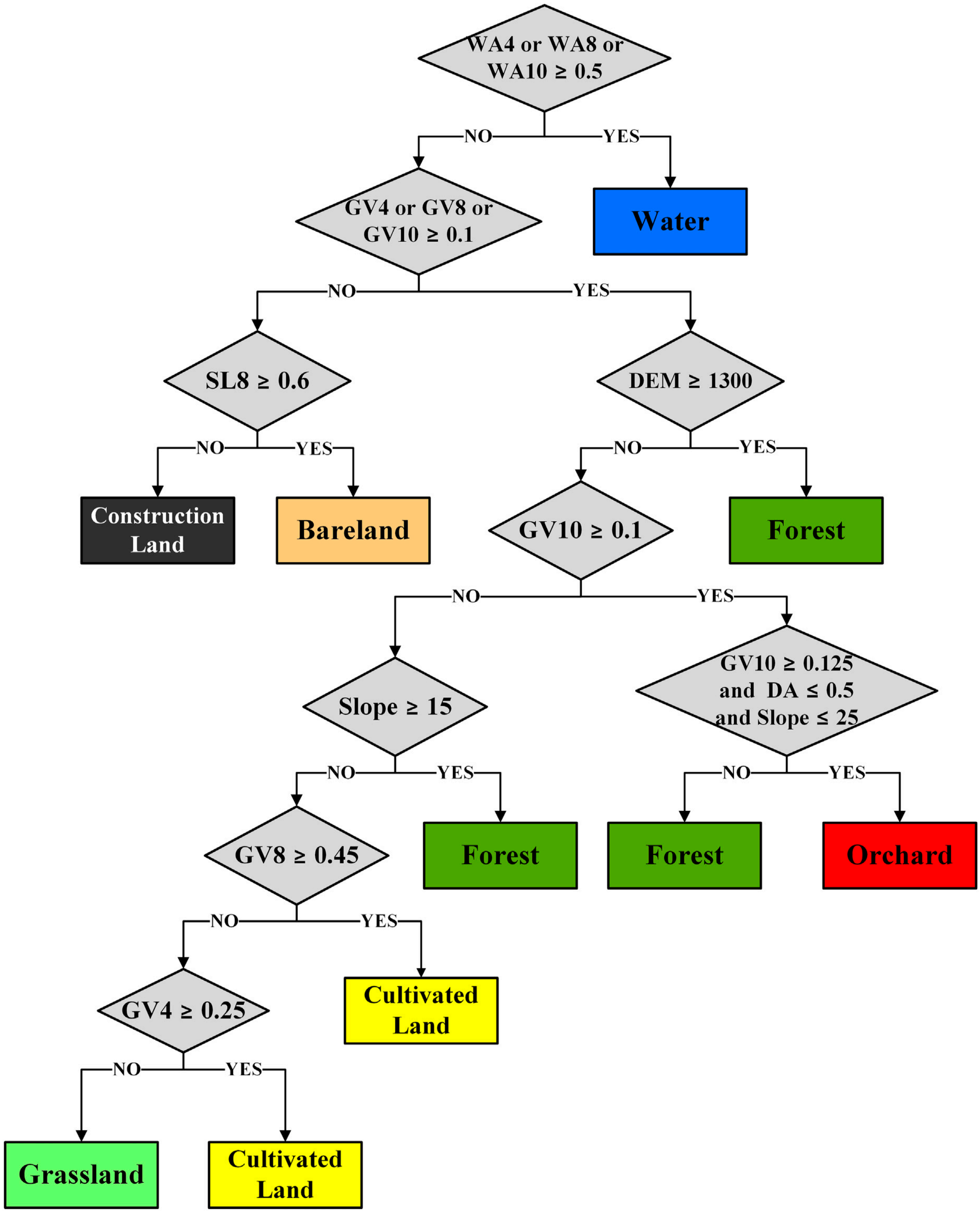

FIGURE 4
The land use/cover classification decision tree in this study.

(1) The water area is extracted by the three seasonal EMA of WA, and the threshold values are WA4 or WA8, or WA10 ≥ 0.5.

(2) The vegetation area and non-vegetation area are divided by the three seasonal EMA of GV, and the threshold values are GV4 or GV8, or GV10 ≥ 0.1.

(3) The bare land and construction land within the non-vegetation area are divided by the summer EMA of SL, and the threshold value is SL8 ≥ 0.6.
(4) The orchard, forest, grassland, and cultivated land are divided by the autumn EMA of GV, and the threshold value is GV10 ≥ 0.6.
(5) Using slope and elevation to further extract forest, and the threshold values are DEM ≥1,300 m and slope ≥15.
(6) Using slope and autumn EMA of GV and DA to further divide the orchard and forest, threshold values are GV10 ≥ 0.125 and DA ≤ 0.5, and slope ≤ 25.
(7) The grassland and cultivated land are divided by spring and summer EMA of GV, and the threshold values are GV8 ≥ 0.45 and GV4 ≥ 0.25.

2.5 Driving force of orchard expansion

2.5.1 Evaluation indicator system

While factors like soil condition, topography and climate have a more localized impact on orchard expansion, regional development has a more external socioeconomic impact. Thus, the influencing factors were selected at the pixel and regional scale and from natural and social dimensions. The evaluation indicator system was shown in Table 3. Due to the favorable climate condition for apple planting, climate change is not considered as the chief factor for local orchard expansion. Therefore, at the pixel scale, the factors were selected from three perspectives of terrain, soil and field conditions, including elevation, slope, soil organic matter, pH, surrounding land types. In terms of social factors, we considered the transportation convenience, the distance to the urban areas and the water sources, which influence the human management processes of irrigation, harvesting and fertilization. At the regional scale, four impact factors, namely average elevation, average elevation standard deviation, average slope and average slope standard deviation, were selected to reflect the differences in natural conditions of each township. For social factors, the population and agricultural output were selected to reflect the differences in socio-economic development of each township. In summary, a total of 17 impact factors were selected to explore their driving effects on orchard expansion.

2.5.2 Random forest regression

Random forest is a machine learning algorithm proposed by Breiman. (2001), which can be used to conduct classification and regression (Tang et al., 2022). It consists of many independent decision trees, and each decision tree is constructed as a random sampling process (Song et al., 2022). The regression algorithm obtains the average of the regression results of all decision trees as the final model output. Then, the random forest regression can quantitatively assess the feature importance and partial dependence based on the existing data through modeling (Liu et al., 2021). The feature importance of each factor is an important parameter, which reflects their relative contributions to the dependent variable. Partial dependence can explain how one or two factors influence on the identified outcome of a machine learning model (Friedman, 2001). In this study, the feature importance is to investigate different influencing factors to orchard expansion. And the partial dependence is to explain the marginal effect of each influencing factor on the orchard expansion (Heilmayer and Brey, 2003). They are both especially suited for the investigation of the forces that influenced agricultural land evolution, particularly when delving into its complex, non-linear driving processes. Therefore, a random forest regression was chosen to explore the mechanisms behind the orchard expansion dynamics in the Loess Plateau. The analysis was performed using the “sklearn” package in Python.

2.6 Orchard planting suitability evaluation

Orchard location decisions and policy suggestions can benefit from a better understanding of the spatial connection between orchard planting suitability and orchard expansion. The suitability evaluation of orchard planting is divided into two parts, including land suitability and climate suitability. According to the soil environment and geographical conditions of the Loess Plateau, 13 indicators were selected considering land conditions, soil conditions, fertility status and climate conditions. Soil is the fundamental factor, providing moisture and nutrients for the growth of orchard cultivated. Topographical conditions are closed related to the growth of apple tree. The difference in elevation, slope and aspect can have a great impact on sunlight exposure, irrigation and soil erosion. Climatic conditions are also key factors, which strongly determine the phenological period of orchard planting. Due to data limitations and a lack of meteorological data at the orchard scale, we use meteorological station data for spatial interpolation, and use the natural breakpoint method for suitability classification. The specific evaluation indicators system was shown in Table 4. Based on the actual state of orchard planting in the study area, the opinions of local experts, and related literature and standards, the indicators affecting the growth of apple tree were divided into three classes: highly suitable, moderately suitable and generally suitable. The weight of the index is determined by the analytic hierarchy process in this study. According to the evaluation indicators system, all raster data were resampled and projected into the CGS_WGS 1984. Finally, we used the spatial analysis tool in ArcGIS 10.2 to predict the distribution of orchard planting suitability. The equation is as follows:

$$\boldsymbol{S} = \sum_{i=0}^{n} \boldsymbol{w_i} \times \boldsymbol{u_i}$$

where S is the comprehensive score of the orchard planting suitability evaluation; w_i is the weight of the i factor; u_i is the score of the i factor; and n is the number of evaluation factors.

TABLE 3 Descriptive statistics of the selected Evaluation indicator of orchard expansion.

Scale	Dimension	Indicators	Average	STD	Max	Min
Pixel	Topography	Elevation (m)	1,126.1	85.7	1,240.8	929.1
		Slope (°)	7.0	1.8	10.7	5.0
		Aspect	171.7	15.8	198.0	145.6
	Soil	Soil organic matter (g/kg)	13.0	1.3	16.2	10.7
		PH	8.1	0.1	8.3	8.0
		Soil type	—	—	—	—
	Neighborhood information	Proportion of adjacent forest (%)	66.1	10.5	86.4	48.9
		Proportion of adjacent farmland (%)	4.7	2.2	10.7	1.8
	Reachability	Distance from water (m)	6,189.1	3,977.8	17,198.5	907.1
		Distance from main roads (m)	2,062.9	1.699.5	9,044.5	723.6
		Distance from urban area (m)	19,502.0	11,397.1	47,254.7	4350.1
Regional	Topography	Average elevation (m)	1,095.1	121.3	1345.6	882.0
		Standard deviation of elevation (m)	96.0	23.3	158.5	71.8
		Average slope (°)	13.2	2.3	19.4	9.5
		Standard deviation of slope °	7.6	1.0	10.8	6.2
	Socio-economic	Total Population	18,616.1	14,882.9	68,395.0	3758.0
		Agricultural output (Billion)	1.2	0.6	3.4	0.3

TABLE 4 The evaluation indicators system for orchard planting suitability.

Dimension	Indicators	Highly suitable (0.8, 1]	Moderately suitable (0.6, 0.8]	Generally suitable (0, 0.6]
Land suitability	Elevation (m)	900~1,200	<900	>1,200
	Slope (°)	3~10	<3∪(10, 15]	>15
	Aspect	135~225	[90, 135)∪(225, 270]	[0, 90)∪(270, 360]
	PH	6~8	—	<6∪>8
	Soil type	[loessal soil, alluvial soil]	dark loessal soil	—
	Soil organic matter (g/kg)	>20	10~20	<10
	Nitrogen (mg/kg)	>0.9	0.6~0.9	<0.6
	Phosphorus (mg/kg)	>20	8~20	<8
	Potassium (mg/kg)	>200	120~200	<120
Climate suitability	Temperature (∘C)	8.5~12.5	[5, 8.5)∪(12.5, 16]	<5∪>16
	Precipitation (mm)	500~800	800~1,500	<500∪>1,500
	Minimum summer temperature (∘C)	13–18	[11, 13)∪(18, 25]	<11∪>25

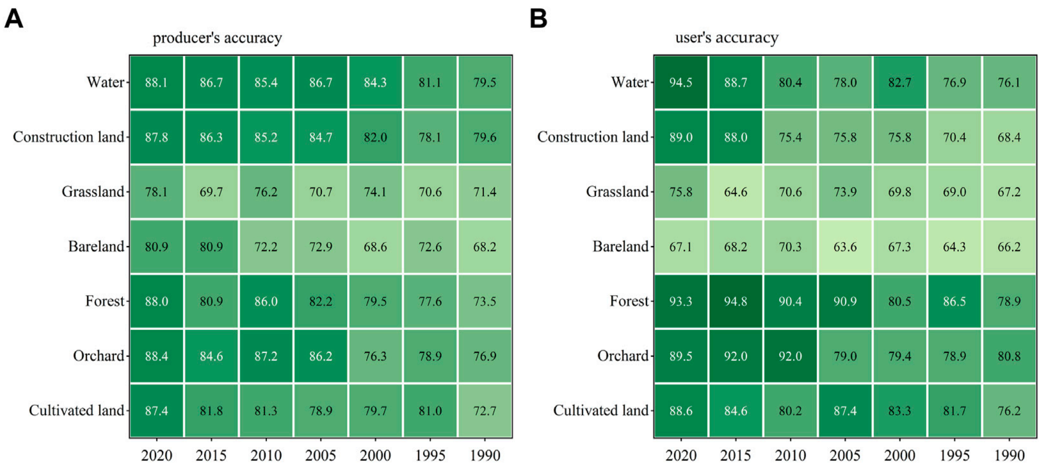

FIGURE 5
Accuracy verification of land use/cover classification from 1990 to 2020. **(A)** Producer's accuracy; **(B)** user's accuracy.

3 Results

3.1 Land use/cover classification and accuracy verification

Our findings indicated the LSMA model combined with the decision tree had great applicability for multi-year land use classification, especially for identifying orchard expansion. The land use/cover classification results of the study area from 1990 to 2020 were presented in Figure 6. The accuracy verification (Figure 5) was carried out based on independent random sampling validations obtained from the field survey. The overall accuracy of classification results from 1990 to 2020 ranged from 74.2% to 86.0%, with kappa coefficients ranging from 0.70 to 0.84. The producer's accuracy and user's accuracy of orchards, cultivated land, water bodies and forest were above 72%.

As shown in Figure 6, the study area has more than 80% of forest throughout all time periods. While the cultivated land dropped year over year and the size of construction land and water did not vary significantly. On the contrary, the orchard and grassland showed an overall increasing trend. In particular, the orchard experienced the greatest increase from 1990 to 2020, tripling in the total area from 1990 to 2020. Orchards now account for 7.94% of the total area, up from 2.94% in 1990. For the three counties, Luochuan, Fuxian, and Huangling, their orchard areas are currently 4.5, 2.1, and 1.8 times larger than they were in 1990, while Luochuan County experiencing the most growth. Comparatively speaking, the cultivated land shrunk by a total of 27,610 ha, representing 71% cultivated land of the study area in 2020. In Luochuan and Fuxian counties, the amount of cultivated land declined by 12,098 and 15,315 ha, with 49% and 46% decreased rate, respectively. The amount of bare land, water bodies, and construction land has increased year by year while the amount of grassland has fluctuated downward.

According to the analysis of land use transfer matrix, the cultivated land, which has been converted to orchards with a total of 32,309 ha, accounts for 49.2% of total orchards. This is followed by forest, with a total of 11,833 ha converted to orchards in the study area, contributing 18% of the total orchards. With 16,254 ha of cultivated land turned into orchards, Fuxian converted the most cultivated land, contributing 67.1% to its current orchard area. Huangling and Luochuan converted 1,452 and 14,603 ha of arable land into orchards over the three decades, contributing 17.2% and 58.9%, respectively. The fastest land use change occurred between 1990 and 2000, when 81,116 ha were primarily transferred from arable land to orchards. The rate of change in land use from 2000 to 2010 is comparable to that from 1990 to 2000. From 2010 to 2020, the rate of land use change slowed down, with just 1,694 ha of arable land being converted to orchards.

3.2 Orchard expansion characteristics

3.2.1 Spatiotemporal characteristics

We found that the orchard area increased rapidly in the first fifteen years but increased slowly in the last fifteen years during the study period (Figure 7C). The whole study period can be divided into two stages: 1) rapid growth stage: from 1990 to 2005. Due to the encouragement of the local government in the process of reform and opening up, the apple planting area in the study area increased from 24,338 ha to 51,379 ha, an increase of about 111%. The orchard area of Fuxian, Huangling and Luochuan increased by 13,298, 3,151 and 10,592 ha, with growth rate up to 158%, 38% and 101%, respectively; 2) volatile growth stage: as the

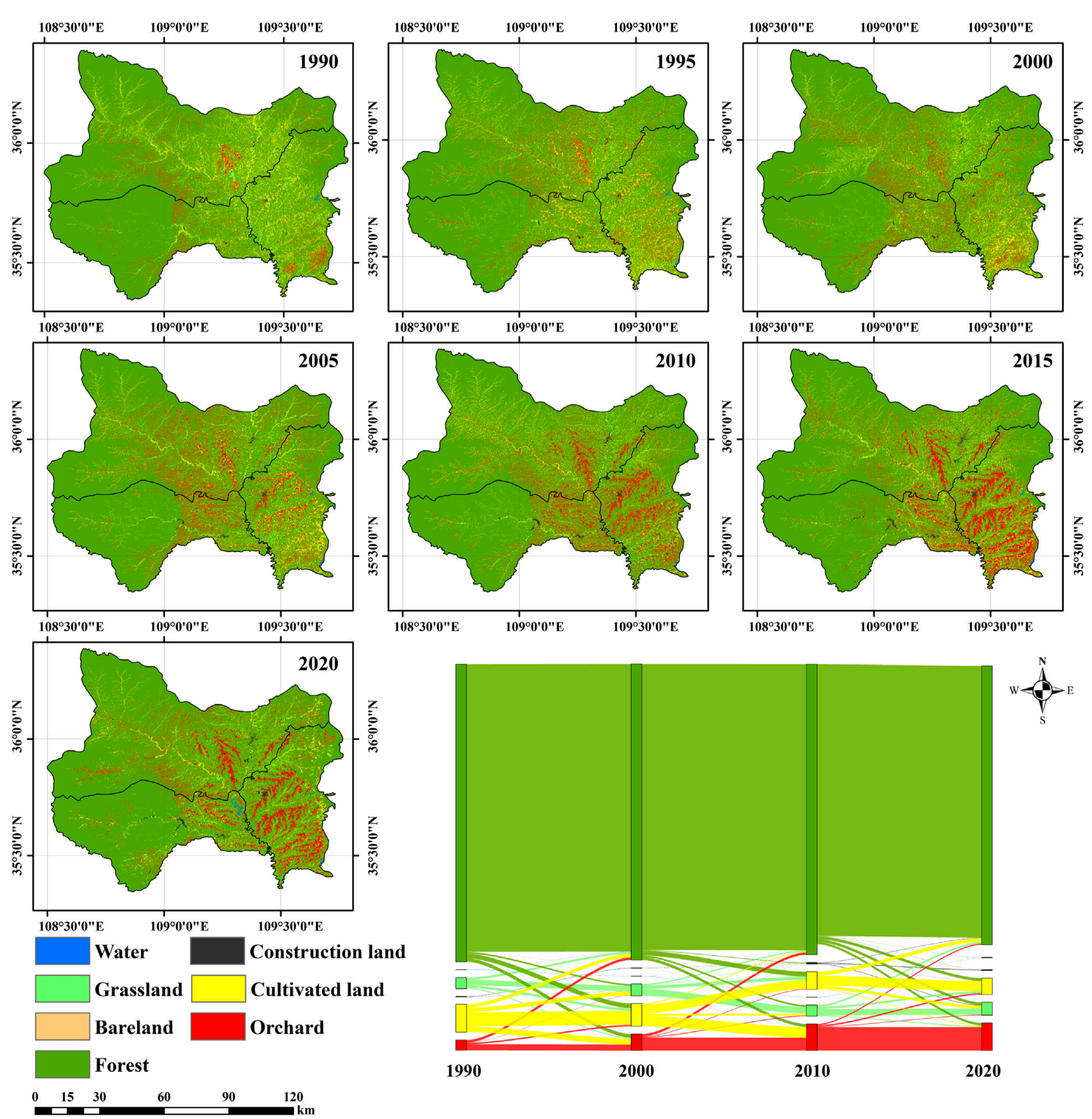

FIGURE 6
Land use/cover classification of the study area and the land use transfer matrix from 1990 to 2020.

areas suitable for apple cultivation were gradually occupied, the expansion gradually slowed down. From 2005 to 2020, apple orchard increased by only 14,267 ha. In 2020, the total area of orchards in the study area was 67,646 ha, of which the orchard area in Fuxian, Huangling and Luochuan were 18,140, 6,735 and 29,296 ha, respectively. The orchard planting area of Luochuan has always been larger than that of Fuxian and Huangling, but its growth rate has gradually decreased. The expansion rate of orchards in Huangling has gradually exceeded that of Luochuan. The planting area of each county has increased by more than 300%.

Due to the local policies and climate change, orchard expanded continuously between 1990 and 2020, initially to the northeast, then to the southeast, and finally to the northwest. In the horizontal direction, the spatial geometry center (SGC) of the orchard shows the trend of eastward expansion before 2010 and

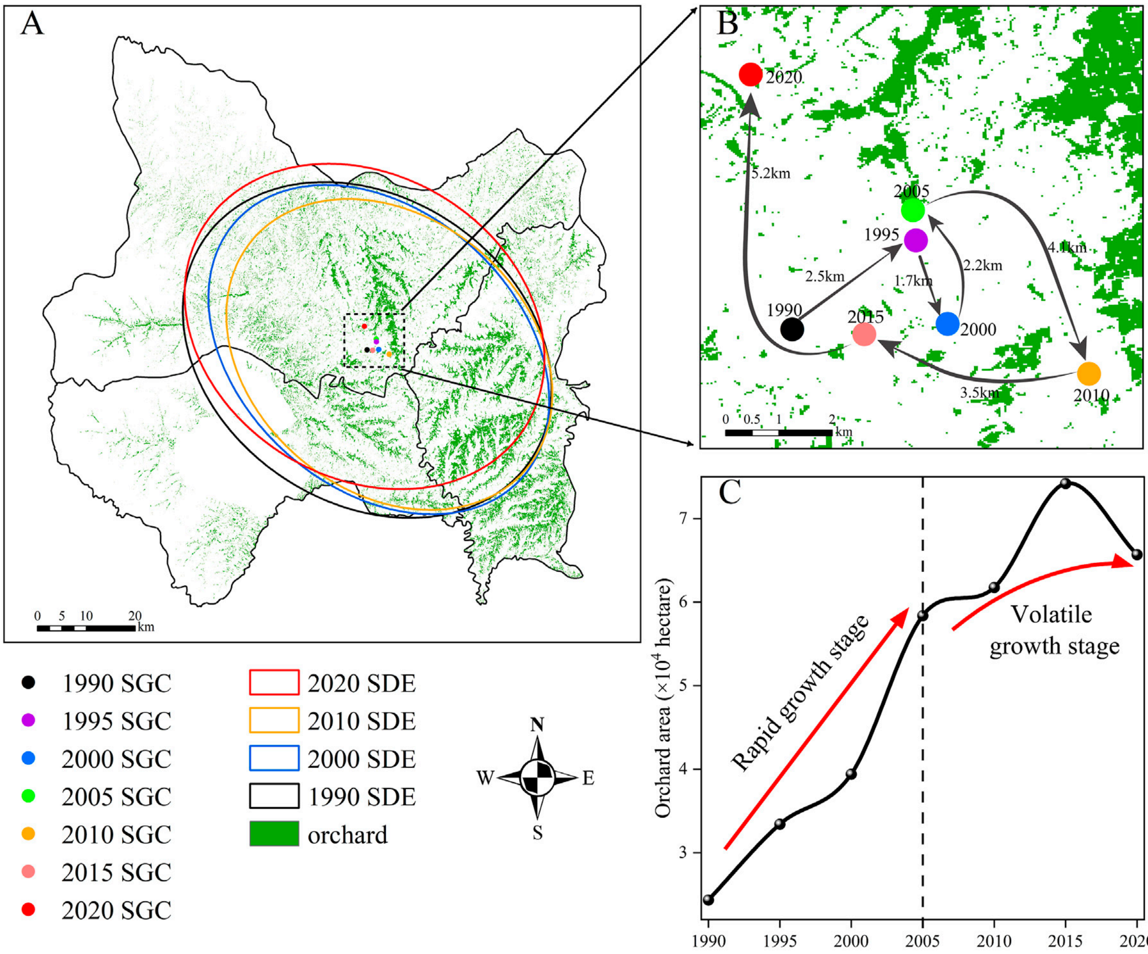

FIGURE 7
Standard deviation ellipse (SDE) analysis and total area growth of orchard. **(A)** The SDE and its SGC of orchard from 1990 to 2020. The ellipse represents the gathering direction. **(B)** Shift in SGC and its shifting distance. **(C)** Growth trend of orchard area in the study area and two stages were divided according to its growth rate.

then shows the trend of westward expansion. In the vertical direction, the SGC of the orchard generally shows a trend of expansion to the north (Figure 7B), with a shifting distance up to 5.2 km from 2015 to 2020.

3.2.2 Physical geographical feature

Orchard expansion has been increasingly occurring in areas at elevations of 600–900 m and above 1,200 m. We divided the elevation into three intervals of 600–900 m, 900–1,200 m and above 1,200 m based on the natural breakpoint method. The characteristics of orchard expansion at these three elevation intervals were studied in 1990, 2000, 2010 and 2020, respectively. Overall, from 1990 to 2020, orchard expansion mainly occurred in the area at 900–1,200 m, with an expansion area of 33,273 ha and growth rate up to 213% (Figure 8A). As a result of favorable soil, light and rainfall, as well as convenient proximity to transit hubs, apple orchards have primarily settled in a region between 900 and 1,200 m in altitude. Higher quality land resources at lower elevations are mostly used by residents for food production and housing, hence the orchard planting area around 600–900 m elevation was the smallest in the area. Besides, we found that the expansion of orchard was most obvious in the area at 900–1,200 m elevation between 2000 and 2010. However, the area at 900–1,200 m, which is the most suitable area for orchard planting, was gradually filled with orchards.

Slope is one of the most important factors to consider in apple planting. According to the natural-geographical conditions of the study area, we divided the slope into three intervals of 0–3°, 3–10°, and 10–15°, respectively. It is clear from Figure 8B that the orchards in the study area are mainly distributed in the area with slopes of 3–10°. Analyzing the characteristics of orchard expansion in each period, we found that the orchards in the study area expanded significantly to the area with slopes of

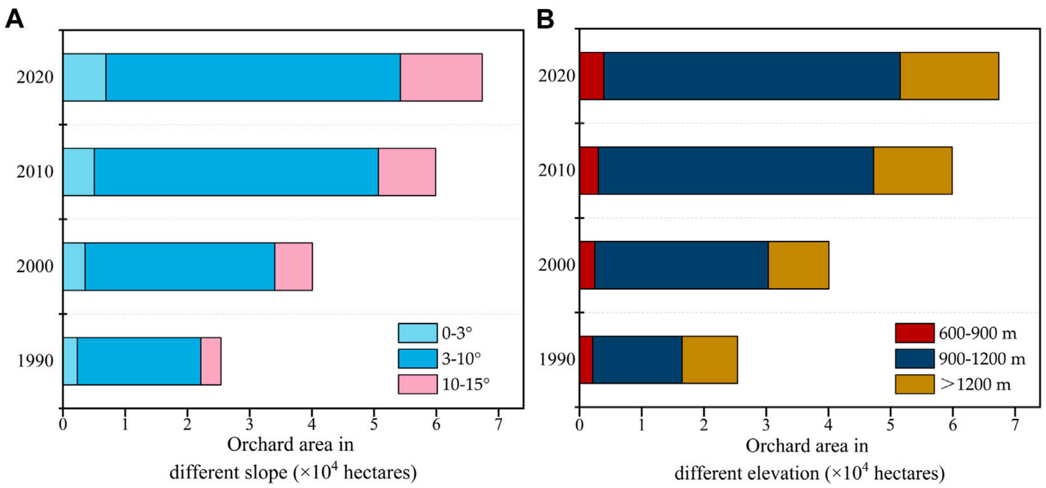

FIGURE 8
Variation in orchard expansion with elevation and slope. **(A,B)** Shows the orchard area under different slope and elevation, respectively.

3–10°from 1990 to 2010, and the expansion rate decreased after 2010. In contrast, the trend is reversed for slopes of 0–3° and 10–15°.

3.2.3 Landscape pattern analysis

In this study, we used landscape metrics to analyze the landscape pattern of orchard planting area. As a whole and for different land use/cover types, we selected 6 and 4 landscape metrics, respectively. The ecological significance of each landscape metrics is shown in Supplementary Table S1.

The number of patches (NP) and patch density (PD) in Fuxian, Luochuan, and Huangling counties increased between 1990 and 2020, with 17.9% and 17.2% growth rate, respectively (Supplementary Table S2). The ratio of the area of the largest patch to the total landscape area (LPI) decreased by about 5%. The landscape shape index (LSI) increased by 3%. The spread ability index (CONTAG) decreased from 62.31 to 60.28. The Shannon Diversity Index (SHDI) increased by 5%. The above results show that from 1990 to 2020, with the expansion of orchards, the land use type of the study area changed greatly. In addition, human activities have increased the landscape's complexity and fragmentation, while also having an impact on the biological environment.

From Figure 9, it can be seen that the number of patches (NP) of orchards continued to increase by about 63.8% during 1990–2020, while the patch density (PD) continued to decrease. Meanwhile, these two indices of cropland had completely opposite trends to those of orchards. The shape indices (LSI) of all categories decreased during the study period, indicating that the landscape shapes of all categories are becoming simpler. The separateness index (SPLIT) of grassland, forest land, and arable land increased during the study period, while the separateness index of orchard decreased. Based on the above results, it can be concluded that between 1990 and 2020, the orchards were characterized by larger planting areas, more aggregated patches, less fragmentation, and simpler shapes. However, a decline in arable land and a more dispersed pattern of grassland, forest, and cropland have resulted from the expansion of orchards.

3.2.4 Orchard expansion varied with planting suitability

Orchards can be planted across the entirety study area, as shown by the planting suitability assessment, with the exception of a few spots at elevations above 1,200 m. The planting suitability evaluation of land suitability evaluation indicators were shown in Supplementary Figure S1. The highly land suitable areas for orchard planting in the study area are mainly concentrated in the central and southwestern parts. The total highly suitable area is 335,371 ha, accounting for about 39.1% of the study area, while the moderately suitable and generally suitable account for 35.1% and 25.8%, respectively. The suitability zones in the north western part of the study area are more dispersed, mainly due to the large variation in soil texture types. The overall climatic suitability of the study area is excellent, with highly suitable regions accounting for over 80%. This is due to the fact that the average annual rainfall and average temperature are in the optimum range for orchard cultivation, thus having a positive effect on apple cultivation. Orchards were primarily dispersed in regions with high suitability, with 84.5% of the total orchard area in 2020. Over the last three decades, orchards expanded mainly into highly suitable regions, covering 37,839 ha, followed by 3,347 ha in moderately suitable regions and 2,006 ha in generally suitable regions.

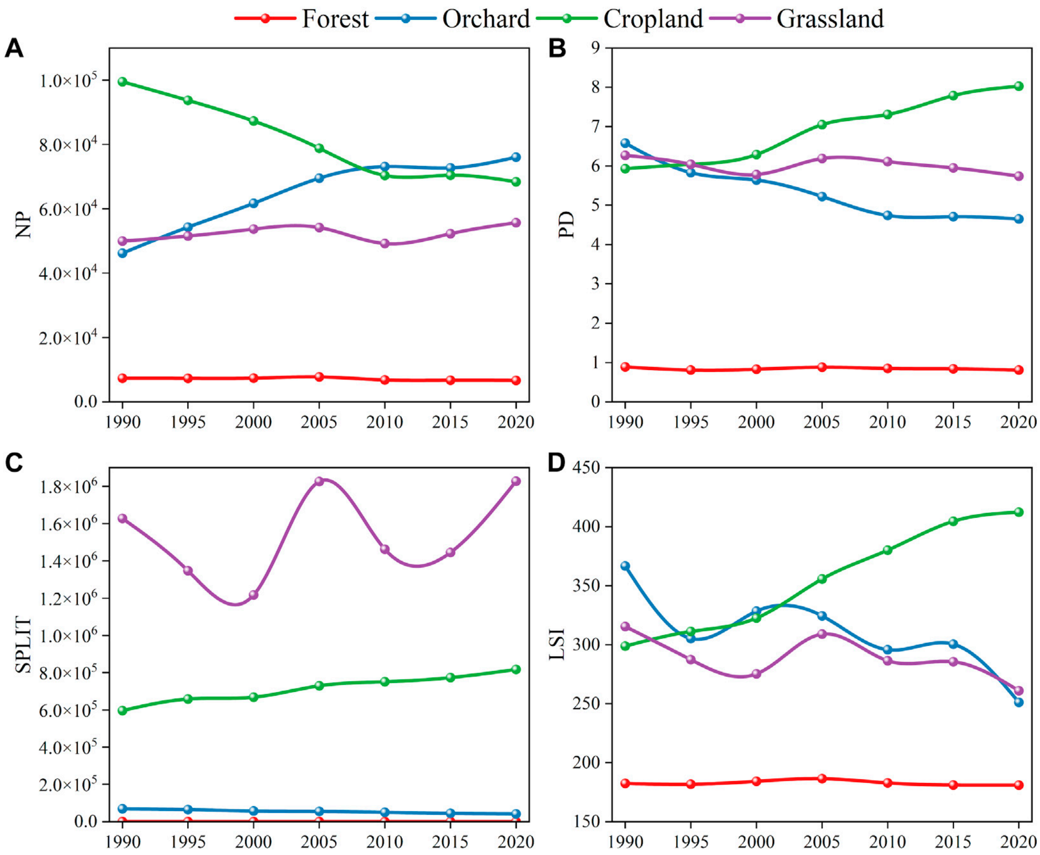

FIGURE 9
Evolution landscape metrics of different land use. Four landscape metrics were selected, including NP, PD, SPLIT and LSI. **(A–D)** Shows the evolution results of four land use types, including forest, orchard, cropland and grassland.

For the three counties, Figure 10 shows the dynamics of orchard distribution in different suitability zones during the period 1990–2020. In the high suitability zone, Luochuan increased its orchard area by 16,431 ha, surpassing Fuxian and Huangling. Although the overall plantation suitability of the study area is good, orchard expansion is nevertheless concentrated in the most suitable regions, implying their inherent strong connection. In recent years, orchard expansion has gradually slowed down and the highly suitable areas of orchards are already at capacity.

3.3 Driving forces analysis

3.3.1 Feature importance

Among all the 17 factors, the slope, proportion of adjacent farmland, agricultural output, aspect, distance from main road and standard deviation of elevation made a great contribution to orchard expansion, with the sum of their feature importance up to 70% (Figure 11A). In particular, slope, aspect and standard deviation of elevation are all topographic factors and their total feature importance is up to 50%. These findings demonstrated that topographical factors are the primary motivator for orchard expansion, of which slope is the most notable attribute due to its highest feature importance. The feature importance of soil pH, distance from urban area, soil texture type, distance from water source and the proportion of adjacent forest are less than 5%. For the remaining factors, we detected few contributions to orchard expansion.

3.3.2 Partial dependence

Figure 11B presents the quantitative relationship between the orchard expansion and the first six influencing factors. When the slope is larger than 10°, the orchard expansion significantly slowed down, implying the orchard expansion is mainly concentrated in the area with slope below 10°. Due to the policy of arable land protection, the magnitude of orchard expansion gradually decreases with the increase of the proportion of adjacent farmland. At present, the orchard expansion mainly occurs in those regions where neighboring

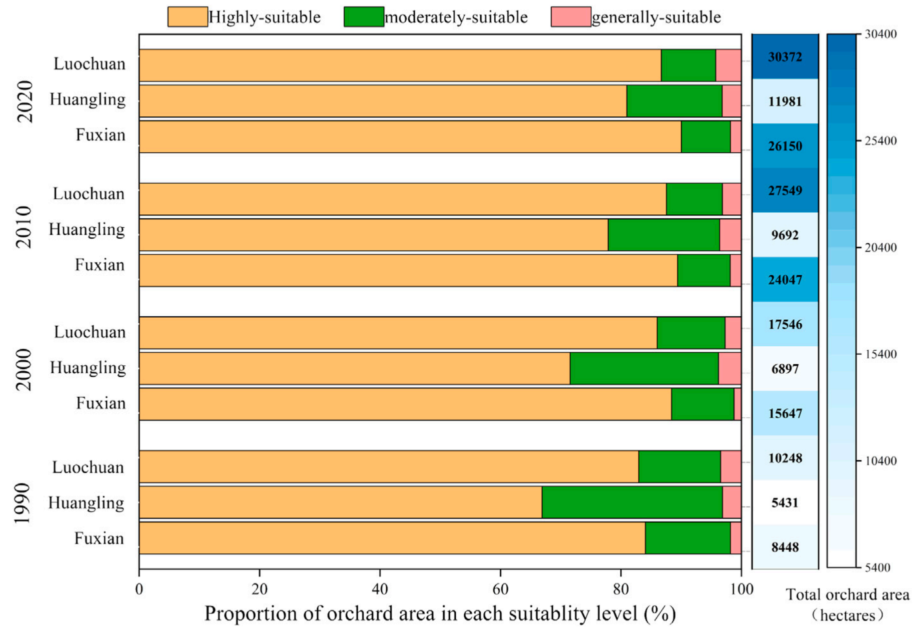

FIGURE 10
Dynamics of orchard area in Fuxian, Huangling and Luochuan under different suitability levels.

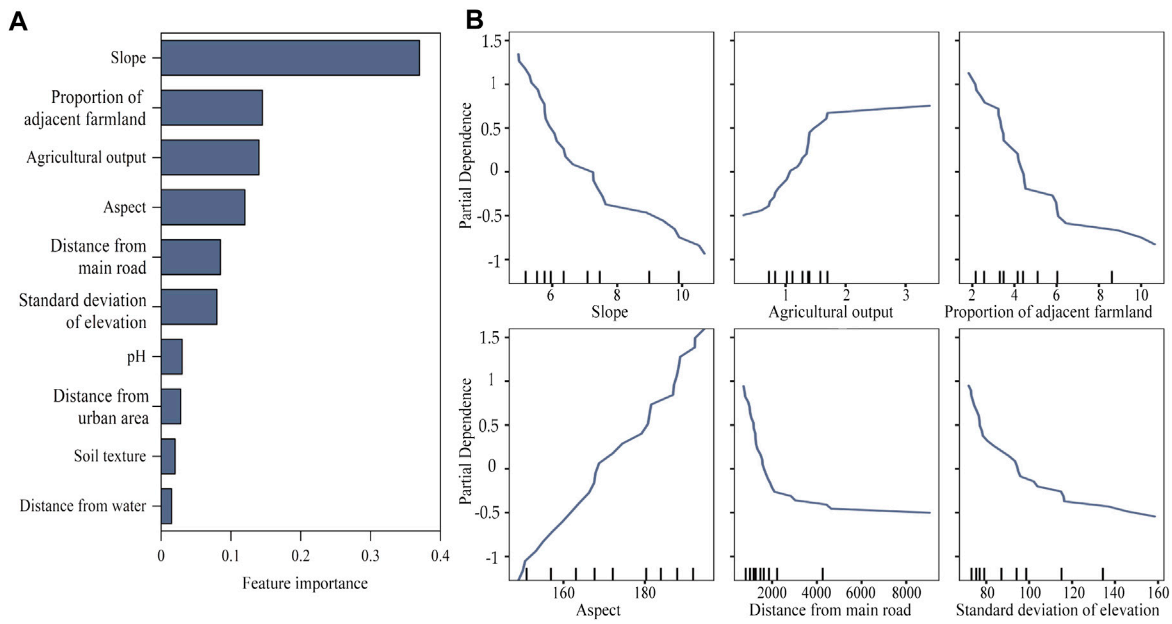

FIGURE 11
Feature importance and partial dependence of selected influencing factors on orchard expansion. **(A)** Shows the feature importance of primary influencing factors on orchard expansion. **(B)** Shows the partial dependence of the first six influencing factors.

cultivated land is below 6%. The relationship between the orchard expansion and aspect tends to be a fixed straight line, but there is no clear expansion pattern. With the increase of the distance from the main road, we observed a downward and then flat trend. In other words, the larger the distance from the road, the less likely the orchard will expand under a threshold of 2 km.

When the distance exceeds 2 km, the orchard area tends to stabilize and transportation will no longer influence orchard expansion under such circumstances. On the contrary, an upward and then flat trend was observed with the increase of the local agricultural output. When the value is between 0 and 160 million-yuan, orchard area will increase rapidly due to the development of social economic development. The orchard expansion changes in two stages with the increase of the standard deviation of elevation of the township. Before the standard deviation of elevation of the township grows to 120 m, the orchard expansion decreases rapidly. After reaching 120 m, the expansion decreases at a slower rate. This is mainly due to the fact that the township with relatively large elevation standard deviation distributed many mountainous areas with large slope, which are not suitable for orchard planting.

4 Discussion

4.1 Orchard expansion and suitability evaluation

Assessing the suitability of orchard plantation can provide valuable instruction for the sustainable expansion of orchards (Pimenta et al., 2021; Arab and Ahamed, 2022). At present, with the rapid development of society, along with land use conflicts, the implementation of the scientific assessment of planting suitability not only helps to improve the efficiency of land use but also enables a rational land allocation. As people's diets change, the demand for fruit is increasing. In order to promote economic development, the local government has adopted different policies to motivate fruit farmers.

In this study, the suitability evaluation results confirm that over 80% regions were highly suitable. It is unsurprisingly to find that the majority of orchards (84.5%) were located in highly suitable areas in 2020. Our findings demonstrate a robust positive relationship between farmers' land-use decisions and local environment condition. Land suitability has been proved to be the crucial factor driving the expansion of local orchards, especially slope. Thus, regional policy guidelines are supposed to focus on improving land suitability. Besides, more social factors, such as infrastructure development and regional incentive strategies, need to be taken into account. Those measures are of tremendous help in places where slope is relatively higher.

In addition, areas with highly suitable orchards are facing the problem of aging orchards, which need to be renewed (Hou et al., 2021). Identifying aging orchards and improving orchard yields are other issues that need to be further addressed. Blind orchard expansion is not the only solution to enhancing economic performance, but the renewal of aging orchards in highly suitable areas deserves more attention. Not only will this raise farmers' incomes and orchard yields, but it will also help rationalize the use of land resources and strike a balance between economic development and ecological conservation.

4.2 Policy recommendations for orchard expansion

The orchard expansion in LP is hugely affected by topographical circumstances. Cultivating apples on the suitable slope will guarantee their yield and quality. Based on the analysis of suitability evaluation, the most suitable slope for apple plantation in the region is 3–10°. To boost the profitability of apple production, local authorities should encourage farmers to grow apples in optimal locations and increase access to agricultural expertise.

In addition, our findings revealed the distance of the orchard from water sources, major roads and urban areas were also key factors influencing the orchard expansion. The cultivation, harvest, and transportation of apples are profoundly influenced by the transportation accessibility. In order to reduce the apples losses during long-distance transit, the government is obligated to improve public infrastructure development in various locations. Besides transportation can be centralized, and apple purchasing markets should be established within an appropriate distance from orchard locations. At the same time, the government should organize the purchase in the fields or in households during the harvest season.

Soil conditions are another essential consideration for apple growth. With the large expansion of orchards, the biological environment of soil was greatly impacted by the excessive intake of pesticides and fertilizers. Emphasis on the application of organic fertilizers can promote the circular ecological agriculture. The government should formulate policy standard for pesticides control and apply scientific fertilization in conjunction with tree growth. This can be a potential external incentive factors driving the orchard expansion. However, such policy related impact factors were not included in this study. In the future, relevant policy projects, poverty alleviation funds and other associated policies should be considered, which can provide more valuable insights for orchard planting in the future.

5 Conclusion

In this study, the land use/cover classification of three typical orchard planting counties on the Loess Plateau from 1990 to 2020 was mapped based on the combination of the LSMA model and the decision tree method. According to the standard deviation ellipse analysis, landscape metrics, physical geographic features and planting suitability assessment, we analyzed the spatiotemporal dynamics of the orchard expansion over the past three decades. From the perspective of environment and socioeconomic, we then developed an evaluation indicator system of potential determinants on orchard expansion. The random forest regression was carried out to quantify the feature importance and partial dependence of those factors. Furthermore, we investigated the evaluation of orchard planting suitability in order to put forward favorable policy suggestions. Our study aims at providing empirical references for the sustainable and synergistic development of agricultural land and economic boom in the ecological fragile region.

The results demonstrate that the orchard has expanded rapidly over the past 30 years, especially between 1990 and 2005. The orchards continued to spread out towards the northwest, and their spatial geometry center migrated from the southeast to the north central area, with decreased fragmentation. In the last 30 years, orchards mainly expanded to highly suitable areas, which totally reached up to 37,839 ha, with a growth rate up to 197%. The natural conditions served as the chief factor to orchard expansion, among which slope contributed the most. Our results revealed the most suitable slope for orchard planting in the study area is 3–10. Therefore, for areas with more hilly and mountainous terrain, gentler slope should be preferred for orchard planting. At the same time, the transportation convenience and the policy support for agriculture also provide a "non-negligible" reference basis for future orchard planting.

Compared with previous studies, this study focused on the ecologically fragile areas of the Loess Plateau from the view of natural geographic characteristics, landscape pattern and orchard planting suitability. Our study provided novel approach for identifying cash crop expansion in ecologically fragile areas. Besides, this study explored the driving factors of orchard expansion from multiple scales by applying machine learning regression, which was innovative compared with previous studies. However, policy related impact factors were not included in this study. In the future, relevant policy projects, poverty alleviation funds and other associated policies should be considered, which can provide more valuable insights for orchard planting in the future.

Data availability statement

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

Author contributions

Conceptualization ZL; Data curation, ZL, QH, and XG; Formal analysis, ZL, QH, XG, and SW; Funding acquisition, ZL and FL; Methodology, ZL, QH, XG, SW, and QW; Software, QH and XG; Supervision, ZL and FL; Validation, YQ and WZ; Writing—original draft, ZL, QH, XG, SW, and QW; Writing—review and editing, ZL, QH, XG, SW, QW, YQ, and WZ. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by the Open Fund of Key Laboratory of Urban Land Resources Monitoring and Simulation, Ministry of Natural Resources, grant number KF-2020-05-026 and the National Natural Science Foundation of China (No. 41801202, No. 41911530693).

Acknowledgments

Thanks to the reviewers and editors for their valuable suggestions for improving the manuscript.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2022.1097236/full#supplementary-material

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 09 January 2023
DOI 10.3389/fenvs.2022.1091898

Determining urban–rural coordinated development in major grain-producing areas based on urbanization and cultivated land use efficiency coordination level: A case study in Hunan Province, China

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SPECIALTY SECTION
This article was submitted to Land Use Dynamics,
a section of the journal
Frontiers in Environmental Science

RECEIVED 07 November 2022
ACCEPTED 30 November 2022
PUBLISHED 09 January 2023

CITATION
Wei X, Liu L, Yuan C and Xia Z (2023), Determining urban–rural coordinated development in major grain-producing areas based on urbanization and cultivated land use efficiency coordination level: A case study in Hunan Province, China.
Front. Environ. Sci. 10:1091898.
doi: 10.3389/fenvs.2022.1091898

Urbanization and cultivated land use coordination is the key to urban–rural coordinated development, especially in the major grain-producing areas in China, but it is rarely examined. A coordination framework of urbanization and cultivated land use efficiency systematically clarified how to achieve Urbanization and cultivated land use coordination. Taking Hunan Province as an example, this study explored the spatiotemporal evolution of the level of Urbanization and cultivated land use coordination from 2000 to 2018 at the county level, identified current types of Urbanization and cultivated land use coordination and discussed the key optimization measures for different types. The results showed that 1) urban–rural coordinated development, abstractly represented by the Urbanization and cultivated land use coordination in major grain-producing areas, depends on the intensity of interactions and the level of integration of urbanization and cultivated land use systems. 2) From 2000 to 2018, the level of Urbanization and cultivated land use coordination in Hunan changed from serious maladjustment to great maladjustment to coordination. 3) The current Urbanization and cultivated land use coordination pattern in Hunan Province has a strong spatial differentiation, which can be divided into eight subregions. The key to the coordinated development of each type is to accelerate the flow of elements through deepening reform and innovation mechanisms to complement the shortcomings of development. This study will provide a scientific reference for the effective implementation of regional coordinated development strategies in major food-producing regions.

KEYWORDS

urban-rural development, urbanization, cultivated land use efficiency, spatiotemporal evolution, zoning, China

1 Introduction

With global urbanization and industrialization, drastic changes have occurred in industrial, employment and social structures in urban and rural areas (Dadashpoor and Alidadi, 2017; Quan et al., 2019; Zhou et al., 2020), giving rise to problems such as rural decay, false urbanization and an imbalance in urban–rural relations (Liu and Li, 2017; Cai et al., 2019; Cai et al., 2021). As one of the fastest growing urbanized countries, China faces even more serious pressures of urban–rural imbalance (Ji et al., 2019). In response, the Chinese government has successively formulated several major national strategies since the beginning of the new century, such as new-type urbanization, rural revitalization, and urban–rural integration (Zhang and Lu, 2018). Urban and rural areas are complex territorial systems with complementary structures and coupled functions (Liu et al., 2020; Delgado-Viñas and Gómez-Moreno, 2022). Urban–rural relationships refer to the interactive symbiotic relationship between urban and rural areas, which cover urban–rural economic, social, ecological, spatial and humanistic aspects (Zhang and Lu, 2018; Liu et al., 2020). A good urban–rural relationship plays an important role in the development of cities and villages (Tacoli, 1998; Yang et al., 2021). For example, stronger rural–urban connectivity is generally associated with higher overall agricultural inputs and yields (Boudet et al., 2020). Urban–rural coordinated development, which is essentially a stage in the evolution of urban–rural relationships, is regarded as the optimal state and eventual form of the urban–rural relationship (Torreggiani et al., 2012; He et al., 2019; Baffoe, 2020). Understanding the variability of contemporary rural–urban interactions could provide insight into future urban–rural coordinated development.

Large population but limited cultivated land is the basic national condition of China. In order to respond to the increasing demand, the efficiency of cultivated land use must be improved. The importance of cultivated land in promoting the stable development of rural areas cannot be overstated. As the main livelihood for rural people, cultivated land use (CLU) activities widely exist in rural areas, especially in food-producing areas (Gollin, D. (2010) Cultivated land is an important input into agricultural activities, such as agricultural cultivation, livestock production and NR-based collection. And high CLUE reflects the realization of the value of cultivated land resources in agricultural production (Kuang et al., 2020). Cultivated land is also essential for the sustainable development of urban systems in terms of providing raw materials and agricultural products, especially potential development space (Zhou et al., 2021). Many urban enterprises rely on demand from rural consumers, and access to urban markets and services is often crucial for agricultural producers (Tacoli, C, 1998). Therefore, high cultivated land use efficiency (CLUE) is fundamental for sustainable development in urban and rural regions (Cao and Birchenall, 2013; Liu et al., 2016; Duan et al., 2021). In this respect, urbanization and cultivated land use coordination (UCLUC) have profound implications for coordinated urban–rural development. However, urbanization characterized by population and industrial agglomeration may have positive or negative effects on the cultivated land use system (Satterthwaite et al., 2010; Oueslati et al., 2019; Boudet et al., 2020), which promotes the heterogeneity and dynamics of UCLUC. Hence, it is necessary to review and clarify the spatiotemporal evolutionary laws of UCLUC, scientifically determine the current situation of UCLUC, and better formulate adaptive policies for regions to promote sustainable development of urban and rural areas.

Scholars in various fields have focused on urban–rural coordinated development, including its definition (Tacoli, 1998; He, 2018; Baffoe, 2020) and mechanisms (He et al., 2019; Liu et al., 2020), measurement and evaluation methods (Li and Liu, 2021; Yang et al., 2021), effects (Mayer et al., 2016), and optimization strategy (Adugna and Hailemariam, 2011; Ma et al., 2021). The evaluation of urban–rural relationships has been examined from multiple perspectives, such as urban and rural welfare (Azam, 2019), ecological networks (Xiao et al., 2017), public investment (Calabro and Cassalia, 2018), and tourism relations (Slocum and Curtis, 2017). Most quantitative studies have adopted comprehensive index systems in the evaluation of urban–rural integration. Rao and Gao (2022) proposed a systematic evaluation index system of urban-rural integration from four dimensions of economy, space, society and environment (Rao and Gao, 2022). Wang et al. (2016) evaluated the relationship between urban and rural areas from the perspective of "income-consumption-productivity" (Wang et al., 2016). Shen et al. (2012) applied a set of critical indicators consisting of benefit indicators and fairness indicators to evaluate the contribution of infrastructure projects to coordinated urban–rural development (Shen et al., 2012). In terms of the measurement model of urban–rural relationships, scholars have mostly adopted the coupling coordination degree model (Song and Tao, 2022), deviation coefficient model (Liu et al., 2017), and decoupling model (Zhu et al., 2020; Cai et al., 2021). Scholars have basically reached a consensus that China's urban–rural relations have undergone a gradual shift from separation and opposition to coordination and integration (Yang et al., 2021). These achievements have greatly contributed to integrated urban–rural development and have laid a solid foundation for our research. However, few studies have explored urban–rural coordinated development from the perspective of UCLUC, particularly using panel data from major grain-producing regions (Bai et al., 2018).

In this paper, we utilize Hunan Province, one of the major grain-producing areas in China, as the research case. The objectives of this study are to 1) construct a theoretical framework of UCLUC from the perspective of synergy; 2) explore the spatiotemporal evolution of the level of UCLUC

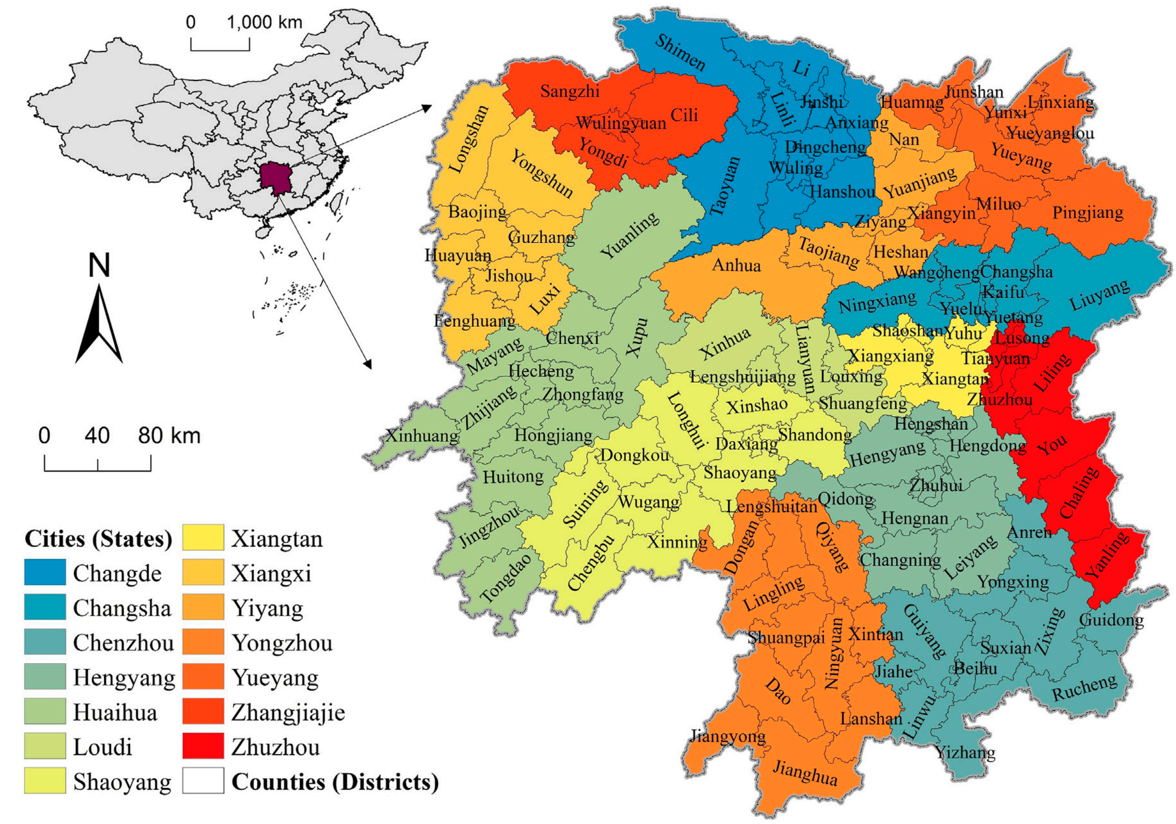

FIGURE 1
Location and administrative division of Hunan Province in China.

from 2000 to 2018 at the county level; and 3) recognize the current subdivisions of UCLUC in Hunan Province and propose optimal recommendations for different types to promote coordinated urban–rural development. The results can provide a reference for high-quality and sustainable development in major grain-producing areas.

2 Materials and methods

2.1 Study area and data sources

This study takes Hunan Province in China as the research area and counties as the analysis object. Hunan Province is one of the 13 major grain-producing areas in China playing a decisive role in ensuring the effective supply of major agricultural products and one of the key areas to promote the new urbanization strategy (Zhang et al., 2021), which makes it an ideal case area for this study. At present, Hunan Province is still in a stage of rapid development and needs to resolve the conflicts between urbanization and CLU (Luo et al., 2018). The county is the basic unit of China's administrative structure, and current social problems such as uneven development are mainly reflected at the county scale. In addition, promoting county urbanization to accommodate China's urban–rural transition has become a major direction for China's urbanization (Zhang et al., 2022). The 2000–2018 period is chosen and divided by 2009 and 2013 into three stages to reveal the evolutionary patterns of UCLUC. 2009 was the middle breakpoint of the research period, and 2012 was the starting year when China implemented the new urbanization strategy. After 2012, Hunan Province entered the new-type urbanization stage characterized by coordinated development of the population, industry, space, society, resources, and the environment (Yu, 2021).

The area of cultivated land in Hunan Province was 41,500 km^2 in 2018, accounting for 19.59% of the total area (211,800 km^2). Hunan's total population was more than 68 million in 2018, with an urbanization rate of 59.58%, which was a mere 36.22% in 2000. According to the administrative division in 2018, Hunan Province included

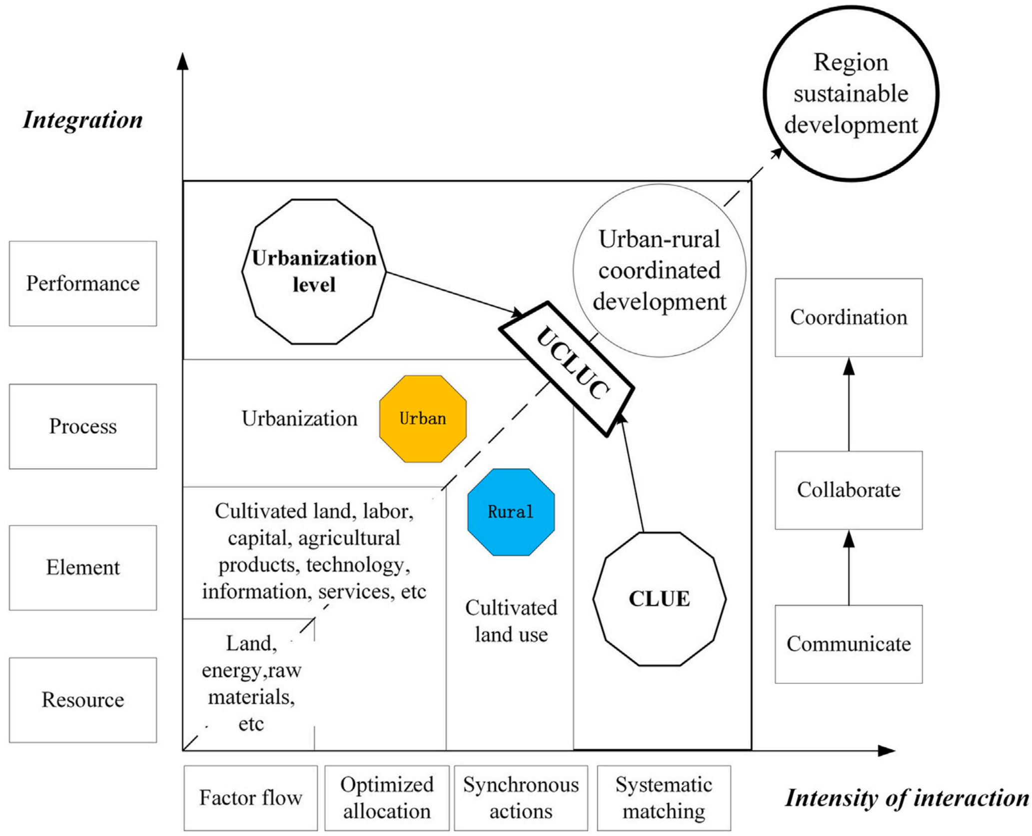

FIGURE 2
Analytical framework of UCLUC.

122 county-level administrative units composed of 36 districts, 19 county-level cities, 60 counties, and seven autonomous counties, which are referred to as counties (Figure 1).

The data sources used in this study are as follows: land use raster datasets, including four phases in 2000, 2009, 2013, and 2018, are used to calculate the spatial urbanization level characterized by the proportion of the urban built-up area. The spatial resolution of the land use data in 2000 is 1 km × 1 km, which is from the resources and environmental platform of the Chinese Academy of Sciences (http://www.resdc.cn/), while in the other three phases, it is 30 m × 30 m from the China Land Surveying and Planning Institute (Wei et al., 2022). We use socioeconomic statistical data to measure the urbanization level and CLUE, including the Hunan Statistical Yearbook (2001–2019) and Hunan Rural Statistical Yearbook (2001–2019). The merger and renaming of administrative divisions are identified based on the administrative divisions in 2018 and combined with time-series data. The mean value method and linear trend method are used for interpolation to deal with some missing socioeconomic data (Song and Tao, 2022).

2.2 A theoretical framework of UCLUC

Although systems and the subsystems that compose them vary widely in nature, the synergy theory, founded by Haken (1983), argues that the qualitative changes in the macroscopic structure of systems are similar, or are even the same. When under the action of external energy or the aggregation state of matter reaches a certain critical value, there will be synergy between the subsystems of any complex system, which will change the system from disorder to order and produce a certain stable structure that evolves to a higher development level of the system (Serrano and Fischer, 2007). Synergetic science is widely applicable because it captures the common characteristics of different systems in the critical process and can describe the transition law from disorder to order in combination with the specific phenomena of each system. Synergetic theory is a strong guide to the study of UCLUC. Many scholars hold the view of coordinated urban and rural development. Caffyn and Dahlström (2005) believed that urban-rural dependencies are a way of supporting sustainable, regional growth. And Yang et al. (2021) point out that urban relationships refer to the interactive symbolic relationship between urban and rural areas that

TABLE 1 Evaluation index system and weight of urbanization.

Urbanization dimension	Indices (Unit)	Index code	Weight
Population urbanization	Proportion of the urban population (%)	PU1	0.060
	Scale of urban population (Person)	PU2	0.033
	Proportion of non-agricultural employed population (%)	PU3	0.039
Land urbanization Economic urbanization	Proportion of urban built-up area in the total area of the region (%)	LU1	0.301
	GDP *per capita* (10,000 Yuan/Person)	EU1	0.129
	Proportion of the output value of secondary and tertiary industries (%)	EU2	0.003
Social urbanization	Total retail sales of social consumer goods *per capita* (10,000 Yuan/Person)	SU1	0.175
	Investment in fixed assets *per capita* (10,000 Yuan/Person)	SU2	0.179
	Number of hospital beds per 10,000 people (Sheets/10,000 persons)	SU3	0.062
	Number of middle school students per 10,000 people (Person/10,000)	SU4	0.019

interactions with and influences each system. In this study, we refer to the collaboration model proposed by Serrano and Fischer (2007) to explain the mechanisms for implementing UCLUC (Figure 2).

Regional sustainable development is accompanied by urban–rural coordinated development (Baffoe et al., 2021), abstractly represented by UCLUC. UCLUC includes two factors: the intensity of interaction and the level of integration, which are represented on the horizontal and vertical axes, respectively. Achieving the integration process includes different stages of the integration of resources, the integration of elements, the integration of processes and finally the integration of performance (Liu, 2018; Yang et al., 2021). Resources are objective natural products, including raw materials, land, water, etc. Elements, the production factors utilized in the process of urbanization and cultivated land use subsystems, are value products transformed by human labor, including tangible (cultivated land, labor, etc.) and intangible (technology, information, etc.) factors. Urbanization and CLU are the main processes in urban–rural systems that we focus on, and urbanization level and cultivated land use efficiency are the results of subsystem actions. Urban–rural coordinated development is achieved by different levels of interaction of elements or systems (Yang et al., 2021). These include element flow, optimized allocation, synchronous actions, and the systematic matching of performances (Fang, 2022). The more integrated an urban–rural system is, the more interactions are necessary or the deeper the intensity of the interactions. The most basic form of interoperation is communication (Boudet et al., 2020; Song and Tao, 2022). The more communication between urban and rural areas, the more activities are executed together and the more aspects need to be coordinated (Tacoli, 1998). The integration process is accumulative: first is resource flow and element optimal allocation to form communication, then comes the integration of processes (urbanization and CLU) to collaboration, and then comes the integration of performances from urbanization and CLUE to firm coordination.

2.3 Estimating the level of urbanization

2.3.1 Developing the urbanization level index

An increasing number of scholars have tended to adopt a comprehensive definition of urbanization to describe the multidimensional characteristics of urbanization (Cai et al., 2021; Yu, 2021). Population, space, economy and society are interrelated and comprehensively reflect the development level of urbanization. Here, we summarize the comprehensive urbanization evaluation system into four aspects, including 10 indices (Table 1). Population urbanization (PU), which mainly reflects the process of a non-agricultural population, is described by PU1-PU3 (Cai et al., 2021). Land urbanization (LU) reflects the process of continuous transformation from agricultural land to urban construction land, described by the proportion of the built-up area (LU1) (Bai et al., 2018; Cai et al., 2021). Economic urbanization (EU) mainly reflects economic development and the non-agricultural transformation of the economic structure, as described by EU1-EU2 (Bai et al., 2018; Yu, 2021). Social urbanization (SU) indicators mainly reflect the social security and lifestyle changes of urbanization, represented by SU1-SU4 (Bai et al., 2018).

2.3.2 Global entropy weight method

The global entropy weight method (GEWM) is used to measure the weight and dynamically analyze the comprehensive urbanization level in Hunan Province. As one of the commonly used and objective assignment methods, the GEWM achieves the measurement of panel data and overcomes the inconsistency between the measurement results of time series data and cross-sectional data compared with the traditional

TABLE 2 Evaluation index system of CLUE.

Variable	Indicators	Index code	Representational meaning
Input	Cultivated areas (ha)	Input 1	Land input
	Agricultural practitioners (10,000 persons)	Input 2	Labor input
	Consumption of chemical fertilizer (ton)	Input 3	Capital investment
	Power of agricultural machinery (kW)	Input 4	Capital investment
Expected output	Total grain output (ton)	Output 1	Social performance
	Total agricultural output value (10,000 yuan)	Output 2	Economic performance

entropy weight method (Yun and Nam, 2021). First, we introduce time series into the cross-section data to construct the initial global evaluation matrix, which includes 10 indices from 122 counties of Hunan Province for 4 years: 2000, 2009, 2013, and 2018. Second, the regularization formula is used to standardize the indices, and then the weight of each index is calculated according to the entropy weight method. Finally, the linear weighting method is used to calculate the urbanization level.

2.4 Estimating CLUE

2.4.1 Developing the index system of CLUE

Efficiency is a state of resource allocation (Paltasingh et al., 2022). CLUE reflects the ability to use various resources and convert them into economic benefits in the process of CLU, which is affected by inputs and outputs (Kuang et al., 2020). Regarding the measurement of CLUE, two main methods are adopted: single factor productivity and total factor productivity. Although single factor productivity can directly reflect the contribution of this factor to output, it cannot comprehensively consider and control the impact of other factors (Zhao et al., 2021). Therefore, we use the latter. We select four input indicators in the categories of land, labor, and capital, such as cultivated land area, and two expected output indicators in the categories of economic and social benefits (Table 2). These indicators are selected based on their relevance to CLUE reported in recent research (Hou et al., 2019; Zhao and Zhang, 2019; Kuang et al., 2020; Zhao et al., 2021).

2.4.2 SBM-DEA model

Data envelopment analysis (DEA) is an objective evaluation method based on the relative effectiveness of the production Frontier, which is suitable for multi-input and multioutput efficiency analysis. The best performers have a full efficient status denoted by 1, and usually multiple decision-making units (DMUs) have this "efficient status" from experience, which affects measuring the coordination degree between CLUE and urbanization in our research (Bai et al., 2018). The slack-based model (SBM-DEA) can avoid this situation and discriminate between these efficient DMUs. It first removes the evaluated DMUs from the original production possibility set, then takes the remaining DMUs as samples to construct a new production possibility set and forms a new effective production Frontier; finally, the effectiveness of DEA is determined based on the new Frontier (Tone, 2002). In this study, we use an input-oriented SBM-DEA model under variable returns to scales. The SBM-DEA model can be described as Eq. 1.

$$\begin{cases} \min \theta \\ s.t. \sum_{\substack{j=1 \\ j \neq \lambda_{j0}}}^{n} \boldsymbol{\lambda}_j \mathbf{X}_{jm} + S_m^- = \boldsymbol{\theta} \mathbf{X}_{j0} \\ \sum_{\substack{j=1 \\ j \neq \lambda_{j0}}}^{n} \boldsymbol{\lambda}_j \mathbf{X}_{jk} - S_k^+ = \mathbf{Y}_{j0} \\ \boldsymbol{\lambda}_j \geq \mathbf{0}, S_m^- \geq \mathbf{0},\ S_k^+ \geq \mathbf{0} \end{cases} \tag{1}$$

where S_m^- and S_k^+ are the relaxation variables of input and expected output, respectively; X_j and Y_j are the values of input and expected output in county j, respectively; λ is the weight vector; and θ is the CLUE value. When $\theta < 1$, it implies that the DMUs are inefficient or weakly efficient, while when $\theta \geq 1$, the DMUs are efficient and can be sorted by their effectiveness.

2.5 Evaluation and grading of UCLUC

2.5.1 Evaluation of UCLUC

In the process of rapid urbanization, there is a deviation opposite to coordination between the improvements of urbanization and CLUE (Liu and Li, 2017), which refers to the quantitative mismatching relationship between systems or internal elements of the system. We use the coefficient of variation (CV) to measure the deviation (Pan and Liu, 2014). First, the annual average growth rate of urbanization (U_{tr}) and CLUE (L_{tr}) are calculated according to Eqs 2, 3. Then, the CV of each county at different periods is calculated according to Eq. 4.

TABLE 3 Coordination classification of UCLUC.

CV	Coordination classification
(0.8, + ∞)	Serious imbalance
(0.6, 0.8)	High imbalance
(0.4, 0.6)	Medium imbalance
(0.2, 0.4)	Mild imbalance
(0, 0.2)	Coordinated development

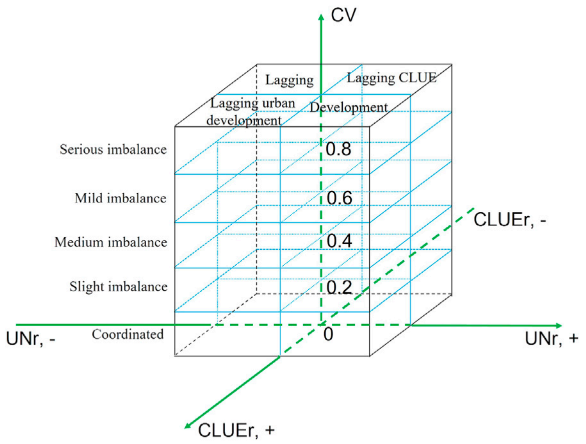

FIGURE 3
Zoning model for different UCLUC types.

$$U_{tr} = \frac{U_{t+n} - U_t}{nU_t} \times 100\% \tag{2}$$

$$L_{tr} = \frac{L_{t+n} - L_t}{nL_t} \times 100\% \tag{3}$$

$$CV = \frac{S}{|\bar{X}|} = \frac{\sqrt{\frac{1}{2}\left[\left(U_{tr} - \frac{U_{tr}+L_{tr}}{2}\right)^2 + \left(L_{tr} - \frac{U_{tr}+L_{tr}}{2}\right)^2\right]}}{\left|\frac{U_{tr}+L_{tr}}{2}\right|} = \left|\frac{U_{tr} - L_{tr}}{U_{tr} + L_{tr}}\right| \tag{4}$$

where U_{tr} and L_{tr} are the average growth rates of urbanization and CLUE, respectively. U_t, U_{t+n}, L_t and L_{t+n} are the urbanization level and CLUE in t and $t + n$ periods, respectively. S is the standard deviation, and $\bar{X}$ is the average value. The smaller the CV is, the smaller the imbalance between urbanization development and cultivated land use, which we refer to as a higher UCLUC.

According to the value of the dispersion coefficient, we divide the UCLUC into five levels, including serious imbalance, high imbalance, medium imbalance, mild imbalance, and coordinated development (Table 3).

2.5.2 Subdivisions of the UCLUC

The scientific diagnosis of the geographic types of UCLUC and their intrinsic causes are of great relevance for promoting sustainable urban and rural development in the new era. Coordinated development represents "stable growth" and "coordinated development". Therefore, the main subdivisions of UCLUC depend on three indicators: the CV value, the growth rate of urbanization and CLUE. Here, the three-dimensional magic cube spatial classification method is used to optimize the zoning of UCLUC (Xie et al., 2021). According to the principle of the three-dimensional tesseract, the CV value, the growth rate of the urbanization level and the growth rate of CLUE are set as the X-axis, Y-axis and Z-axis of the tesseract, respectively, to construct a three-dimensional tesseract. Among them, the CV value is still maintained at five levels, as shown before, and the growth rate of the urbanization level and the growth rate of CLUE are divided into two levels of development and lagging with 0 as an interval. As a result, 20 subdivisions of UCLUC exist theoretically (Figure 3).

3 Results

3.1 Characteristics of urbanization and CLUE

Since the beginning of the new century, the urbanization of Hunan Province has experienced a stage of fast development, rapid development and slow development, and the urbanization subsystem has developed from imbalance to equilibrium (Figure 4A). The urbanization level of Hunan Province steadily increased from 0.131 in 2000 to 0.289 in 2018, with an increase of 0.158 over 18 years and an average annual growth rate of 0.83%. The PU level was the highest in 2009; the SU level was the highest in 2000, 2013, and 2018; and the EU level was the lowest in the whole study period. Specifically, the SU was developing rapidly, reflected in the increase in fixed asset investment (SU2) and healthcare (SU3), while SU4 was in a rapid decline after 2009, which created a highly balanced urbanization state.

The CLUE in Hunan Province was 0.779, 0.740, 0.663, and 0.739 in 2000, 2009, 2013 and 2018, respectively (Figure 4B), with a decrease of 0.040 over 18 years and an average annual growth rate of -0.22%. There were three evolutionary trends in the six input–output variables of CLUE in Hunan Province in 2000–2018: the consumption of chemical fertilizer and cultivated land area remained stable; gross agricultural product and total power of machinery experienced rapid increases; and agricultural employees and grain output remained stable (2010–2018) after decreasing and increasing (2000–2009), respectively.

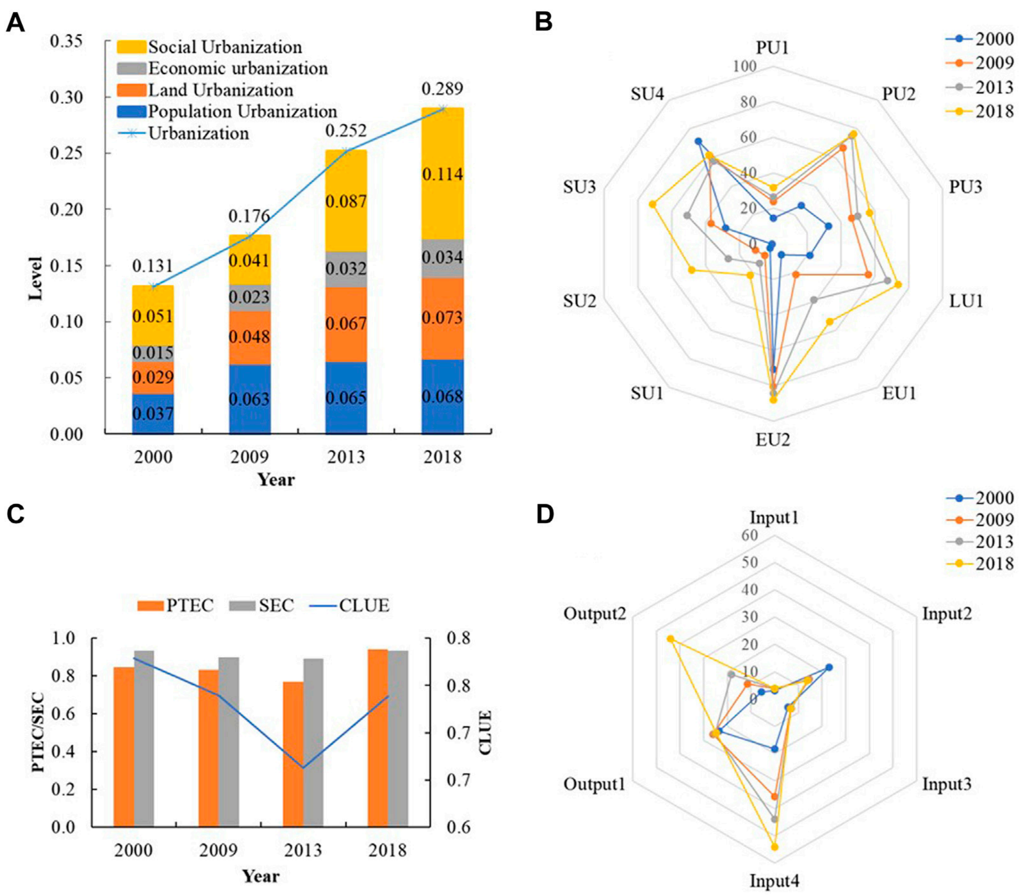

FIGURE 4
Characteristics of urbanization and CLUE in Hunan Province. **(A)**: The characteristics of different urbanization dimensions; **(B)**: The characteristics of urbanization indices; **(C)**: The characteristics of PTE, SEC, CLUE; **(D)**: The characteristics of inputs and outputs of CLUE.

TABLE 4 UCLUC in Hunan Province in different periods.

Periods	CV	Coordination classification
2000–2009	1.347	Serious imbalance
2010–2013	1.634	Serious imbalance
2014–2018	0.132	Coordinated development

3.2 Temporal–spatial characteristics of UCLUC

3.2.1 Dynamic changes of UCLUC

From 2000 to 2018, the dispersion coefficient between urbanization and CLUE in Hunan Province showed a trend of slight expansion and then significant reduction, which increased from 1.347 in 2009 to 1.634 in 2013 and then decreased significantly to 0.132 in 2018, which was in a state of coordinated development (Table 4). This showed that the situation between urbanization and CLUE changed from serious imbalance to coordinated development.

3.2.2 Spatial patterns of UCLUC

From 2000 to 2009, more than 95% of the counties were in a state of imbalance, and only five counties (i.e., Furong, Hetang, Dingcheng, Wulingyuan, and Heshan) were in a state of coordination (Figure 5 and Table 5). During 2009–2013, only one additional county was in a state of coordination compared to the previous period, but the number of counties with serious imbalances was as high as 109, 1.2 times higher than the previous period. These results are consistent with the analysis results at the provincial scale; that is, the overall degree of coordination in Hunan Province deteriorated from 2009–2013. During 2014–2018, the number of counties with coordinated development significantly increased to 27, and the number of serious imbalance counties dropped sharply to 53. Moreover, the counties with coordinated development were mainly distributed in the northwestern and central regions.

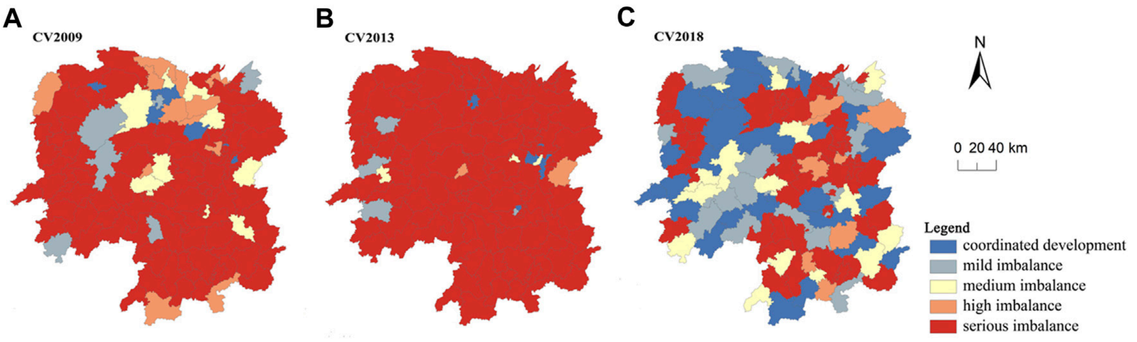

FIGURE 5
Spatial patterns of UCLUC in different periods. **(A)** Spatial patterns of UCLUC in 2009; **(B)** Spatial patterns of UCLUC in 2013; **(C)** Spatial patterns of UCLUC in 2018.

TABLE 5 Statistics of the types of country coordination degrees in different periods.

Periods	Indicators	Serious imbalance	High imbalance	Medium imbalance	Mild imbalance	Coordinated development
2000–2009	Number of counties/ Unit	89	12	10	6	5
	Percentage/%	72.95	9.84	8.20	4.92	4.10
2010–2013	Number of counties/ Unit	107	2	3	4	6
	Percentage/%	87.70	1.64	2.46	3.28	4.92
2014–2018	Number of counties/ Unit	53	8	16	18	27
	Percentage/%	43.44	6.56	13.11	14.75	22.13

3.3 Zoning for coordinated development

As previously discovered, UCLUC had obvious spatial variation. According to Section 2.5.2, there were eight types of UCLUC in Hunan Province from 2014–2018 (Figure 6A): serious imbalance of development (Type Ⅰ), high imbalance of development (Type Ⅱ), medium imbalance of development (Type Ⅲ), slight imbalance of development (Type Ⅳ), coordinated development (Type Ⅴ), serious imbalance with lagging CLUE (Type Ⅵ), serious imbalance with lagging urban development (Type Ⅶ), and slight imbalance of lagging (Type Ⅷ). Their geographic location and limiting factors are summarized based on their numerical characteristics (Figure 6).

Serious imbalance of development (Type Ⅰ): This type of region is distributed in 16 counties, such as Taoyuan and Guiyang, accounting for 13% of all counties (Figure 6A). The region has an average level of urbanization and an abundance of cultivated land resources, but both urbanization and CLUE are at an increasing stage of development (Figures 6B,C). The lack of synchronization between the growth rate of urbanization and CLUE is the main cause of the serious mismatch in the region. Nevertheless, the disparity coefficient is low (i.e., 0.901). High imbalance of development (Type Ⅱ): This region includes eight counties, including Pingjiang and Xintian, and is mainly located in the more peripheral urban areas and areas with richer arable land resources. Medium imbalance of development (Type Ⅲ): The region includes 16 counties (i.e., Yanling), located in the western ecologically fragile areas and areas dominated by agricultural production, which are of high ecological importance and mostly in restricted development zones, resulting in the average annual growth rate of urbanization development being less than that of CLUE (Table. 6). Slight imbalance of development (Type Ⅳ): This area includes 17 counties, such as Changsha, which is mainly located within the radiation circle of city transportation with richer cultivated land and is farther away from the urban center. The traffic axis drives the movement of various factors, such as population and capital, between urban and rural areas, promoting their joint development (Stastna and Vaishar, 2017). As a result, the degree of incoherence is low (i.e., 0.291). Coordinated development

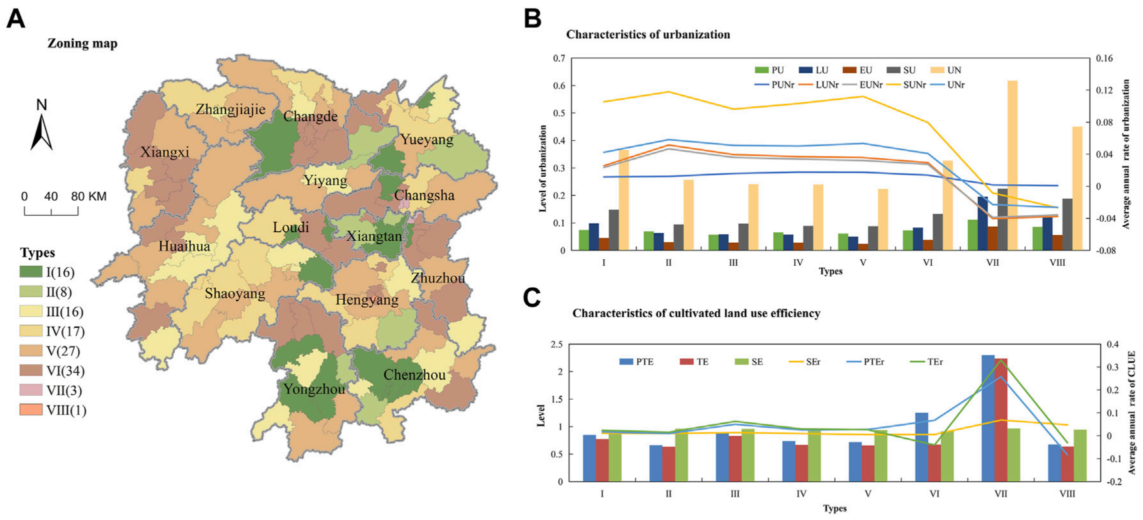

FIGURE 6
Characteristics of different UCLUC types. **(A)** Zoning map; **(B)** Characteristics of urbanization in different subdivisions; **(C)** Characteristics of cultivated land use efficiency in in different subdivisions.

TABLE 6 Geographic location, limiting factors, and key measures of different UCLUC types.

Type	Numerical characteristics			Geographic location	Limiting factors	Key measures
	CV	Unr	CLUEr			
I	0.901	0.042	0.047	More peripheral urban areas; Areas with richer cultivated land resources	Lack of synchronization but a low disparity coefficient	Make full use of transport axes to further connect core cities; Strengthen the connection between urban and rural areas; Guide the transformation of CLU to improve the economic output; Nurture the branding of traditional agricultural products and develop new agriculture
II	0.714	0.058	0.023			
III	0.479	0.051	0.107	Ecologically fragile areas and areas dominated by agricultural production	Development is prohibited because of its ecological importance	Develop low-intensity and high-value ecological agricultural products; Strengthen the integrated development of tourism and agricultural product production
IV	0.291	0.050	0.054	Within the radiation circle of city transportation	Richer cultivated land resources and farther away from the urban center	Promote the systematic and diversified development of rail transport; Strengthening the gradual diffusion of "transport axes"
V	0.096	0.053	0.049	Areas around central cities; Areas with richer land resources	Low growth rate of CLUE and urbanization	Further deepen the reform of the population and land systems to coordinate the free and efficient flow of factors between urban and rural areas
VI	4.191	0.041	−0.035	Core cities; Ecologically fragile areas in the northwest	Rapid urban development "robs" inputs of CLU. In addition, the restriction of CLU.	Limit high-intensity industrialization and urbanization; Optimize the layout of the urban and rural industrial structure; For ecologically fragile areas, the measures are similar to Type III
VII	1.957	0.023	0.472	Four counties: Tianxin, Yuhua, Shifeng and Yanfeng	CLU and urbanization are in the process of drastic transformation	Accelerating the transition process; Deepen the reform of the population management system, such as planning urban public services and infrastructure based on the quantity and structure of the resident population; Optimizing the industrial structure and functional layout
VIII	0.200	−0.026	−0.040			

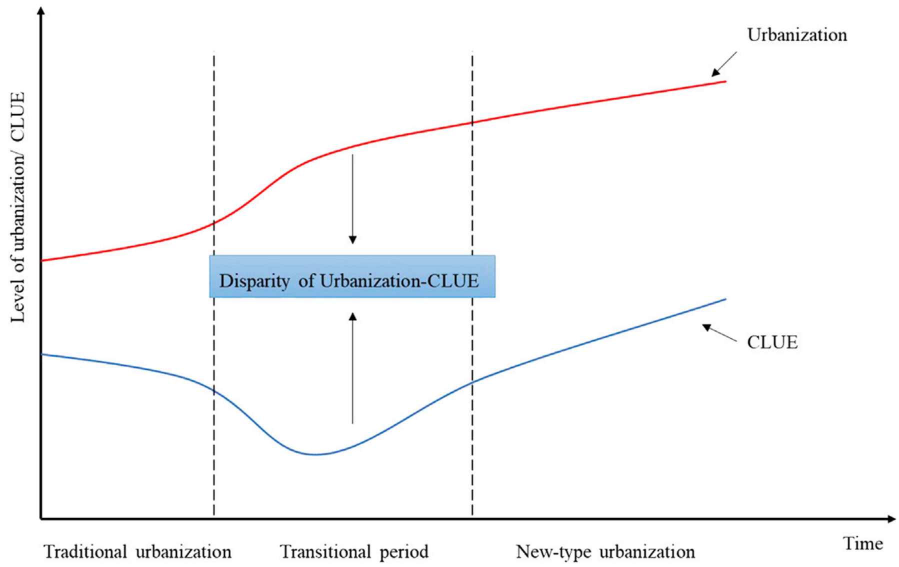

FIGURE 7
Evolution of the level of urbanization and CLUE.

(Type V): There are 27 counties in this type of area, accounting for 22% of all counties. It can be divided into two types of areas: one is the areas with relatively high development intensity around central cities (i.e., Liuyang), and the other is in the areas with richer land resources (i.e., Changde and Huaihua). High imbalance of development (Type VI): This type includes 34 counties, such as Furong and Longshan, which are mainly located in the "Changsha-Zhuzhou-Xiangtan City Group" and the ecologically fragile areas in the northwest (Zou and Wang, 2022). Serious imbalance with lagging urban development (Type Ⅶ): This type of area includes three counties, Tianxin, Yuhua, and Shifeng, which are severely mismatched between different urbanization dimensions and CLUE and are developing slowly. Specifically, only the SU in Shifeng increased, only PU in Tianxin increased, and all dimensions of urbanization in Yuhua decreased (Figure A1). Slight imbalance of lagging (Type Ⅷ): There is only one county (i.e., Yanfeng) of this type, in which cultivated land use and urbanization are in the process of drastic transformation.

4 Discussion

4.1 Evolution of urbanization, CLUE and UCLUC

Hunan Province is a lens through which to observe China's urbanization process and CLUE evolution. UCLUC presents a horizontal rugby shape, which is enclosed by a flat S-shaped urbanization curve and a U-shaped CLUE curve, as shown in Figure 7. The overall level of urbanization has been improving with a flat S-shaped curve, which is an objective law verified by many countries (Mulligan, 2013). At the beginning of the new century, China's guiding ideology was "development is the absolute principle", and social urbanization lagged seriously. In this context, policymakers in Hunan Province were committed to pursuing economic growth, mainly driven by "land finance" and "migrant worker tide" (Gu and Liu, 2012; Lin et al., 2015), and healthcare, education and employment had to make concessions. In 2009, the development of economic urbanization was seriously impacted by the global financial crisis, and the export-led economy was hit hard in Hunan Province (Mi et al., 2017). Meanwhile, the global financial crisis also created development opportunities; a direct result was that the whole country entered the adaptation period of urbanization transformation. Hunan Province turned to increasing infrastructure construction and stimulating domestic demand to drive economic growth. Meanwhile, disadvantages such as unfairness that had accumulated during rapid urbanization gradually erupted. As a revision, a new urbanization strategy was proposed in 2012, marking China's entry into the new urbanization stage (2013–2018). Compared with the traditional urbanization model, new urbanization is characterized as "people-oriented" and attaches importance to the quality of urbanization and the governance of the ecological environment (Yu, 2021). With the adjustment of industrial structure and the strategic adjustment of urbanization development direction, Hunan's economic development recovered from the international financial crisis, and urbanization has tended to be highly balanced while the rate has decreased.

China's urbanization is known as "urbanization at breakneck speed" in human history, and it has changed CLUE considerably (Hou et al., 2019). There is a substitution effect of technology for rural labor in CLU along with urbanization (Zhao et al., 2021), and it has changed from weak to strong. In the early stage of urbanization, the necessary input elements for farmland production, such as the rural labor force and farmland, are rapidly "absorbed" by cities due for rapid urbanization and industrialization (Zhou et al., 2021), resulting in insufficient farmland use inputs, and abandonment and extensive land use behaviors appear in many areas (Su et al., 2020). As urbanization reaches a certain stage, the central government begins to focus on rural development strategies, to give more attention to the multifunctional value and sustainability of agriculture, and to apply the advanced management experience and technology that has emerged with urbanization to the cultivated land utilization system (Hou et al., 2019). As a result, labor-saving inputs such as machinery and pesticides replace the lost agricultural labor. At the same time, the output is also increasing due to yield-enhancing inputs such as improved seeds and management techniques. In addition, because people's consumption awareness is also upgrading, the pursuit of green organic food further guides the input reduction and agricultural structural changes (Chang et al., 2018). Therefore, in the later stage of urbanization, the CLUE begins to improve, and the gap between urbanization and CLUE closely narrows.

4.2 Remove institutional barriers and accelerate the flow of factors

The realization of urban–rural coordinated development is accompanied by the narrowing of the urban–rural gap. The urban–rural gap is mainly reflected in the industrial structure and the public facility services that serve the industrial structure (Azam, 2019). The narrowing of the gap between urban and rural public services and industrial sectors mainly relies on the all-around cooperation of the three major changes: labor transfer, technological progress and changes in consumer demand. These three major changes emerge in the long-term interactions of cultivated land, labor force, agricultural products, technology and other factors (Satterthwaite et al., 2010; Hou et al., 2019; Deng et al., 2020). There is a strong link between the three changes, with technological progress facilitating labor migration, labor migration facilitating the upgrading of consumer demand, and technological progress securing the upgrading of consumer demand. In the context of China, this process of interaction is deeply regulated by institutions, including the national development strategy, the household registration system and the land system (Yan et al., 2018). Because CLU systems are artificial–natural systems, the interactions are also related to geographic location and resource endowments (Figure 8). The policy intervention points to the coordinated development of urbanization and CLUE lies in accelerating the urban–rural flow of factors through policy improvement, promoting the upgrading of the three processes. Specifically, 1) institutional reform and innovation should be deepened to establish and improve a unified urban–rural element market and a mechanism for integrated development, to promote the free flow of elements (people, land, economy, and industry) in both directions between urban and rural areas and to enhance the allocation efficiency of elements. 2) Moreover, it is suggested to promote regional coordinated development by zoning and classification because of diverse basic conditions and development goals, as well as varying rates of development in different regions. According to their development orientation and comprehensive development level, there are eight coordination types in Huan Province, and different promotion strategies should be adopted for each type.

4.3 Policy guidance for UCLUC zoning management

On this basis of mechanisms for urban–rural coordinated development, geographic location and limiting factors, adaptive policies for regions to promote sustainable development of urban and rural areas are proposed (Table 6). For the serious imbalance of development (Type Ⅰ) zones, it is important to fully utilize transport axes to further connect core cities, allowing them to gather population and the economy, to highlight core city development characteristics and to promote high-quality urbanization. At the same time, it should make sensible use of cultivated land resources and scientifically guide the transformation of cultivated land use to improve economic output. Specifically, the advantages of land and labor force in rural areas should be utilized fully, the branding of traditional agricultural products should be nurtured, and a combined primary and tertiary industrial chain based on agriculture should be formed, new agriculture such as eco-agriculture and experiential agriculture should be vigorously developed, and the connection between urban and rural areas should be strengthened. In regard to the high imbalance of development (Type Ⅱ) zones, the causes of development dislocation are similar to those of Type I, and the key measures are similar to those of Type I.

To promote UCLUC in the medium imbalance of development (Type III) zones, its rich ecological resource endowment should be utilized to develop low-intensity and high-value ecological agricultural products and to strengthen the integrated development of tourism and agricultural product production to improve comprehensive CLUE while preserving ecological space.

For the slight imbalance of development (Type Ⅳ) zones, the gradual diffusion of "transport axes" into rural areas should be

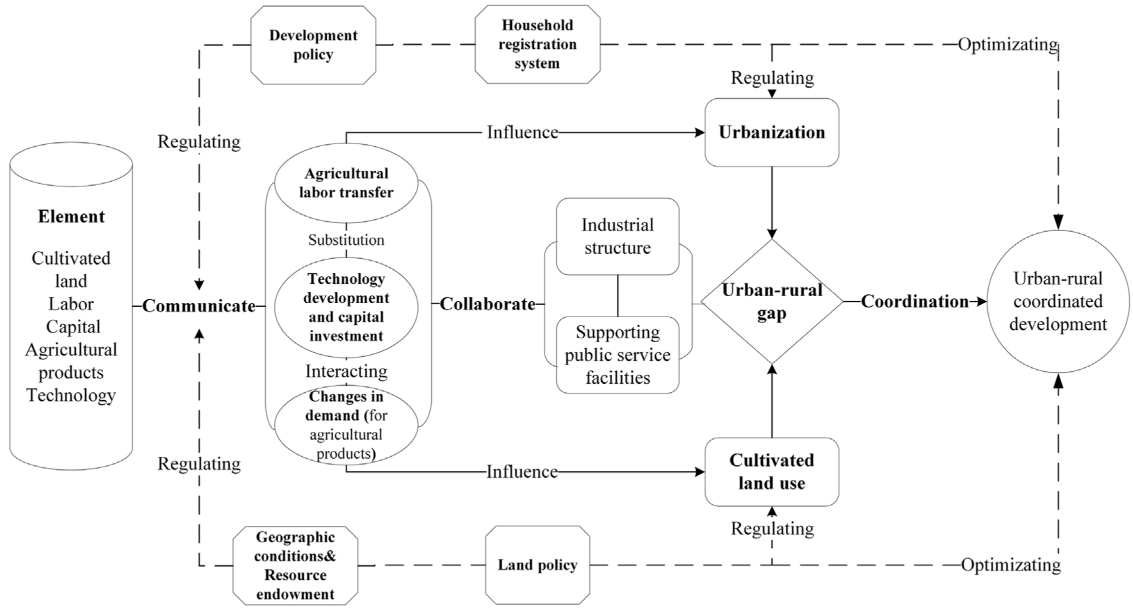

FIGURE 8
Mechanisms for urban–rural coordinated development from the perspective of urbanization and CLUE coordination.

further promoted to improve the efficiency of factor flows and to promote UCLUC in this type of zone. In particular, the construction of urban and rural rail transport should be strengthened, and the systematic and diversified development of rail transport should be promoted (Lu et al., 2019).

For coordinated development (Type V) zones, owing to the location advantage, resources from the countryside provide a good foundation for the development of suburban areas. On the other hand, the capital and technology in cities overflow into rural areas through the trickle-down effect to promote the transformation of cultivated land use from labor-intensive to capital-intensive, which effectively improves CLUE (Zhang et al., 2020). As a result, the region has formed a pattern of coordinated development of urbanization and CLUE. However, the low growth rate of CLUE and urbanization limits its further harmonious development. In the new era, the key to enhancing the UCLUC in this region lies in raising the level of urbanization and CLUE by further deepening the reform of the population and land systems; coordinating the free and efficient flow of people, land, money, industry and other elements between urban and rural areas; improving the efficiency of resource allocation; and finally creating a model for high-level coordinated urban and rural development.

Serious imbalance with lagging CLUE (Type Ⅵ) zones has had a high level of urbanization and a rapid growth rate affected by the radiation of "Changsha-Zhuzhou-Xiangtan City Group" as the leader of economic development in Hunan Province. However, rapid urban development has "robbed" a large amount of cultivated land, rural labor and other resources, leading to a reduction in the input of cultivated land systems, which has led to a slow increase in CLUE (Han et al., 2021). The key to achieving coordinated urban–rural development in the region lies in regulating urban expansion speed and the structure of the industry to the suitable urbanization stage. Furthermore, the relationship between urban–rural development should be regulated by optimizing the layout of the urban and rural industrial structure considering that "population is the carrier of other factors" and "people follow industry". Ecologically fragile areas present a high level of EU and a low level of CLUE due to the restrictions of construction and cultivated land use activities (Zou and Wang, 2022). To promote UCLUC in this region, it should fully utilize its rich ecological resource endowment based on the environmental carrying capacity, insist on protecting the ecological space to develop low-intensity and high-value ecological agricultural products, and strengthen the combination of tourism and ecological agricultural products to improve the comprehensive CLUE. Moreover, the provincial agro-eco-compensation mechanism is recommended to support ecologically fragile areas and narrow the regional development gap.

Type Ⅶ zones are in the transition stage of urbanization from speed to deepening quality, which is characterized by lagging urbanization and serious imbalance. The key to improving UCLUC in this region lies in deepening the reform of the population management system to enhance the inclusiveness of cities for foreign populations (Yang et al., 2019). The quantity and structure of the resident population should be used as the basis for planning urban public services and infrastructure (Wu et al., 2020). Furthermore, the industrial structure and functional layout should be optimized to enhance the city's innovation capacity and core advantages for speeding up and increasing the quality of urban development. The cause of the development disorder of the slight imbalance of lagging (Type VIII) zones is similar to Type VII. Therefore, the governance measures are similar to Type VII; in short, accelerating the transition process.

4.4 Research limitations

In addition to bringing the economic benefits considered in this study, there are certain negative externalities associated with CLU, particularly in ecological terms, such as large amounts of carbon dioxide released (Deng and Gibson, 2019; Kuang et al., 2020). Moreover, the use of green production in agriculture is an inevitable requirement of global modern agricultural development and an important measure to achieve the 2030 sustainable development goal of the United Nations (Xie et al., 2018). Given this, the connotation of CLUE should be expanded, and ecological efficiency indicators should be included to evaluate CLUE in follow-up research.

5 Conclusion

This paper expands on the study of urban–rural coordinated development from the perspective of urbanization and CLUE coordination and proposes an analytical framework for UCLUC. This study measures Hunan's UCLUC level based on estimating the level of urbanization and CLUE and explores the spatiotemporal evolution. On this basis, it identifies the types of UCLUC in Hunan Province and finally proposes optimization policy suggestions to promote coordinated urban and rural development for different types of areas. The results show that from 2000 to 2018, the level of UCLUC in Hunan Province changed from serious maladjustment to great maladjustment to coordination, with the level of urbanization rapidly improving and CLUE first decreasing and then increasing. The high-UCLUC areas were mainly in the northwestern regions of Hunan Province. Eight types of UCLUC are identified in Hunan Province. In the future, targeted governance optimization measures should be taken for different types in the new era. In general, it should unify the urban and rural factor markets, promote the free flow and equal exchange of factors, and strengthen the foundation for UCLUC. Moreover, it is necessary to strengthen the construction of infrastructure such as transportation and networks, improve the level of urban and rural public services, and improve the eco-compensation system to promote the harmonious development of urban and rural areas.

Data availability statement

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

Author contributions

XW: Conceptualization, Methodology, Validation, Visualization, Writing—original draft. CY: Supervision, Funding acquisition, Formal analysis. LL: Conceptualization, Supervision, Writing-review and editing. ZX: Investigation, Writing-review and editing. All authors reviewed the manuscript.

Funding

This work was supported by the National Natural Science Foundation of China (Grant No. 42001224); and the Fundamental Research Funds for the Central Universities of China (Grant No. 2021TC072).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 08 March 2023
DOI 10.3389/fenvs.2023.1134136

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Land Use Dynamics, a section of the journal Frontiers in Environmental Science

RECEIVED 30 December 2022
ACCEPTED 21 February 2023
PUBLISHED 08 March 2023

CITATION
Wang X, Zhou D, Jiang G and Peng C (2023), How can the sustainable goal of cultivated land use in the Qinghai-Tibet Plateau be realized?—based on a research framework of cultivated land use patterns.
Front. Environ. Sci. 11:1134136.
doi: 10.3389/fenvs.2023.1134136

How can the sustainable goal of cultivated land use in the Qinghai-Tibet Plateau be realized?—based on a research framework of cultivated land use patterns

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The study of cultivated land use models is an important means to improve the benefit of cultivated land use and promote the sustainable use of cultivated land. The rational optimization of regional cultivated land use models based on the consideration of regional background conditions and development goals can provide a scientific basis for ensuring the sustainable use of cultivated land. This study constructed a three-dimensional research framework of "natural quality-utilization intensity-spatial layout" of cultivated land utilization pattern. Taking the county as a unit, the natural quality, spatial distribution and utilization intensity of cultivated land in the Qinghai-Tibet Plateau were evaluated, and the types of cultivated land utilization models were determined. Based on the ecological protection and the regulation and control of agriculture and animal husbandry in the Qinghai-Tibet Plateau, the optimization direction of cultivated land use patterns was discussed. The results show that the cultivated land use pattern divided by the "NUS" three-dimensional model can accurately reflect the characteristics of cultivated land use in the Qinghai-Tibet Plateau. The existing cultivated land use pattern in the Qinghai-Tibet Plateau is basically consistent with its ecological protection and development direction zoning, but the problems of unreasonable expansion and excessive use intensity of cultivated land exist in the ecotone between some development areas and restricted areas. Therefore, the utilization and optimization of cultivated land in the Qinghai-Tibet Plateau should be based on the premise of protecting ecological security and striving to solve the contradiction between agricultural development and ecological protection to realize the sustainable utilization of cultivated land.

KEYWORDS

sustainable use, cultivated land use pattern, natural quality, spatial layout, utilization intensity, Qinghai-Tibet Plateau

1 Introduction

As the basic element of agricultural production (Zhou et al., 2021), the utilization and change of cultivated land has always been the focus of global attention (Arowolo and Deng, 2018; Chiemela et al., 2018). According to relevant research, the global population will continue to grow in the future. It is estimated that by 2050, the number of people will exceed 9.8 billion (Chouchane et al., 2018), and the food demand will increase by more than 50%, posing a serious challenge to global food production and ecological protection (Schiefer et al., 2016). In September 2015, the United Nations formally adopted the 2030 Agenda for Sustainable Development. The adoption of 17 development goals fully reflects three aspects, namely, economic development, social progress and environmental protection (Perez-Martinez et al., 2023). Sustainability with environmental protection as its goal requires human beings to adjust the relationship between themselves and the natural environment at any time to match the production development with the carrying capacity of resources and environment. (Bryan et al., 2018; Uusitalo et al., 2019; Bas et al., 2021). The corresponding agricultural development should fully consider the balanced relationship between food production and ecological protection. Especially in the context of China's large population and small land area and the uneven distribution of cultivated land resources, how to correctly and effectively use cultivated land resources should be considered (Ye et al., 2020). Since the reform and opening up, significant changes have taken place in the use of cultivated land in China. The scale of planting has been expanding, and the intensity of utilization has been increasing. Although food production has increased and economic benefits have been brought, problems, such as the decline in cultivated land quality and ecological degradation, caused by the intensive use of cultivated land have become increasingly prominent (Ma et al., 2020; Chen et al., 2021). In the face of the increasingly serious problems of agricultural production and ecological protection in the use of cultivated land, the existing research focuses on how to scientifically select appropriate land use methods for different regions to achieve the goal of sustainable utilization of cultivated land.

The sustainable use of cultivated land requires a reasonable use mode that is suitable for a region's natural and socioeconomic conditions to meet the local food and ecological protection needs in terms of quantity and quality (Wu et al., 2022). The cultivated land use pattern is a differentiated cultivated land use status proposed from a specific research scale and angle under the premise of comprehensively considering natural, social and economic factors (Liu, 2009; Zhang et al., 2019). At present, there is no clear theoretical definition of the concept of cultivated land use patterns in academic circles. Domestic and foreign scholars mostly focus on crop planting structure (Singh et al., 2011; Zhang et al., 2014; Balan et al., 2015; Mesgari and Jabalameli, 2018), farming methods (Dai et al., 2011; Balan et al., 2015; Jayne et al., 2016; Qiu and Wang, 2018), cultivated land use intensity (Chen et al., 2015; Ye et al., 2020), and the number and structure of cultivated land (Fezzi and Bateman, 2011; Yin et al., 2017; Foski, 2019; Zhang et al., 2020; Zhu and Xu, 2020) to define cultivated land use patterns. At the same time, scholars at home and abroad have used methods, such as farmer surveys (Jayne et al., 2016), Gao et al. (2018), (Mastrangelo et al., 2019), landscape indices (Yin et al., 2017; Foski, 2019), and model construction (Singh et al., 2011; Mesgari and Jabalameli, 2018; Ye et al., 2020) to delineate cultivated land use patterns. The research scale of cultivated land use patterns has gradually advanced from the household scale to the regional scale. However, most of the existing researchers describe cultivated land use patterns from a single perspective, the depiction of cultivated land use patterns is relatively simple, and they are mostly based on a certain index or a certain characteristic, such as *per capita* cultivated land area, cultivated land scale, structure, and cultivated land use intensity. While cultivated land is a composite system composed of multiple elements and affected by many aspects, the study of cultivated land use patterns is not only the expression of a single dimension or feature in the cultivated land system but also considers the reflections of different components in the system in various combinations. By studying the cultivated land use model and comparing it with the regional production conditions and development goals, the problem of unreasonable use of cultivated land can be solved at the source to achieve the goal of sustainable development.

The distribution of cultivated land resources in China is quite different, and high-quality cultivated land resources are mostly concentrated in the southeast plains and coastal areas (Xu et al., 2017). Therefore, previous research on the use of cultivated land has mainly focused on the main grain-producing areas, and less attention has been given to ecologically fragile areas with less cultivated land, such as the Qinghai-Tibet Plateau (Fan et al., 2020; Miao et al., 2021; Song et al., 2022). However, with the development of the social economy, the population of the Qinghai-Tibet Plateau is increasing (Gao et al., 2021), and foreign tourism is booming (Yang et al., 2021). The use of cultivated land on the Qinghai-Tibet Plateau not only needs to ensure the goal of food production, but also ecological protection, which is an arduous process. The goal is to rationally arrange the agricultural production space on the Qinghai-Tibet Plateau to balance agricultural production and ecological protection with power.

The Qinghai-Tibet Plateau is sparsely populated, bearing the ecological barrier function of China and even the world. Although its arable land area is small, its proportion in the total agricultural output value is equal to that of animal husbandry (Yang et al., 2019). Since 1980, climate warming has provided conditions for cultivated land reclamation. Social and economic development has prompted farmers and herdsmen to intensify the use of cultivated land. The area of cultivated land on the Qinghai-Tibet Plateau has increased from 956 km^2 in 1990–2,180 km^2 in 2020 (Liu et al., 2021). Under the pressure of long-term cultivated land expansion and intensive use, it is unknown whether the current situation of cultivated land use in the Qinghai-Tibet Plateau meets the local ecological protection requirements. Therefore, this paper constructs a three-dimensional pattern recognition framework of cultivated land use based on "natural quality-utilization intensity-spatial layout" and proposes the optimization direction of cultivated land use in different regions, in combination with the regional development goals of the Qinghai-Tibet Plateau, which provides a reference for the follow-up realization of sustainable use of cultivated land in the Qinghai-Tibet Plateau.

2 Study area and data gathering

2.1 Overview of the study area

The Qinghai-Tibet Plateau is vast and diverse in terrain, with an average elevation of more than 4,000 m. as shown in Figure 1. The main climate type is plateau mountain climate. The average annual temperature of the Qinghai-Tibet Plateau is between −5°C and 15.5°C. The temperature presents a "high low high" distribution pattern from the southeast to the northwest. The average annual temperature difference is 7.37°C. The average annual precipitation is about 415.3 mm. (Chen and Han, 2015). The spatial distribution of precipitation is uneven and gradually decreases from the southeast to the northwest. The precipitation center is located in the Nujiang River basin, Mekong River basin and Yangtze River basin in the southeast. The Qinghai-Tibet Plateau is rich in sunshine, with annual total solar radiation of 140–180 kcal/cm^2, the total annual sunshine hours are 2500–3200 h. (Liang et al., 2013).The main land use of the Qinghai-Tibet Plateau is grassland and forest land. Restricted by terrain, temperature, irrigation and other conditions, the agricultural type is mainly valley agriculture, which is distributed in the One-River-Two-Tributaries basin and the Hung River valley area in the northeastern part of Qinghai Province. Compared with other regions, the temperature is higher, the frost-free period is longer, the heat is relatively sufficient, the terrain is flat, the soil is fertile, the water source is sufficient, the sunshine time is long, the water irrigation, the water and heat conditions are better, and it is more suitable for farming.

2.2 Data gathering and processing

The data used in this paper include land use data, DEM data, soil attribute data, annual average temperature, annual precipitation data, county-level administrative division vector data and agricultural and rural statistical yearbook data in the Qinghai-Tibet Plateau. The land use data came from the national remote sensing monitoring spatial distribution data of land use types from the Chinese Academy of Sciences' Resource and Environmental Science and Data Center and are generated based on manual visual interpretation of Landsat TM images of the United States Landsat, with a resolution of 1 km; the annual average temperature and annual precipitation data are from the spatial interpolation dataset of annual average temperature and annual precipitation since 1980 by the Center for Resources and Environmental Science and Data of the Chinese Academy of Sciences; the county-level administrative division data came from the research results of the second research task of the second comprehensive scientific expedition to the Qinghai-Tibet Plateau; the DEM data came from the data of DEM 30 m by province (SRTM 30 m) in the data center of the Chinese Academy of Sciences; the soil attribute data came from the National Tibetan Plateau/Third Pole Environment Data Center (TPDC); and the agricultural data came from the statistical yearbooks of provinces, cities and counties in the Qinghai-Tibet region.

The DEM data of the provinces and the county-level administrative division data were fused and trimmed to obtain the DEM data of the Qinghai-Tibet Plateau. Some missing soil attribute data were filled by interpolation. The study removed the counties with 0 cultivated land area in 2020 and took the remaining 150 counties as the research object.

3 Methodology

This section is divided into subheadings. It should provide a concise and precise description of the experimental results, their interpretation, as well as the experimental conclusions that can be drawn.

3.1 Theoretical framework construction based on "NUS"

The cultivated land system is a complex system composed of many elements, which constitute an orderly cultivated land resource structure and maintain the balance of the cultivated land system (Hu et al., 2021). The long-term interaction between human agricultural planting activities and the ecological environment on different scales makes the use of cultivated land show various characteristics. It reflects the natural and economic attributes of the cultivated land use system. Its attributes include the natural quality and spatial form of cultivated land, and its social and economic attribute includes the utilization state of cultivated land by human beings. The natural quality of cultivated land is closely related to natural conditions, such as altitude, climate, and soil. It is the basis for determining the spatial distribution of cultivated land and is also affected by human activities. It is a prerequisite for judging whether a region is suitable for agricultural production activities and is the most basic guarantee factor (Cheng et al., 2012; Zhang et al., 2017; Chen et al., 2019). Cultivated land use intensity is a direct reflection of the degree of human utilization of cultivated land and the social and economic benefits and is used to measure the impact of human activities on cultivated land use (Li et al., 2019; Niu et al., 2019). The spatial layout of cultivated land is characterized by the shape and distribution of fields, reflecting the impact of changes in natural conditions and human activities on the distribution of cultivated land resources (Liu et al., 2021). From the perspective of the nature-humanity complex, the natural quality of cultivated land, the intensity of cultivated land use, and the spatial layout of cultivated land are important components of the cultivated land system, which run through the entire process of the development and change of the cultivated land system. Therefore, this study constructs a research framework of characteristics of cultivated land use based on "natural quality-utilization intensity-spatial layout" (NUS), which can reflect the characteristics of cultivated land use in the whole process along with multiple elements, which systematically describe the regional differences in cultivated land use patterns. The research framework is shown in Figure 2.

Agricultural sustainable development refers to the agricultural development pattern of resource conservation, environmental friendliness, industrial efficiency and farmers ' income increase in agriculture. To achieve sustainable agricultural development, we must first grasp the existing state of cultivated land use. The NUS framework combines the natural quality, utilization intensity and spatial layout of cultivated land, identifies the corresponding cultivated land use patterns, evaluates the overall cultivated land use status of the region, and determines the priority of regional agricultural development, which can provide a realistic basis for the rational utilization of cultivated land resources. The cultivated land utilization model identified under the NUS framework can enable the Qinghai-Tibet Plateau to develop regional characteristic agriculture according to local conditions, make full use of cultivated land resources on the basis of environmental

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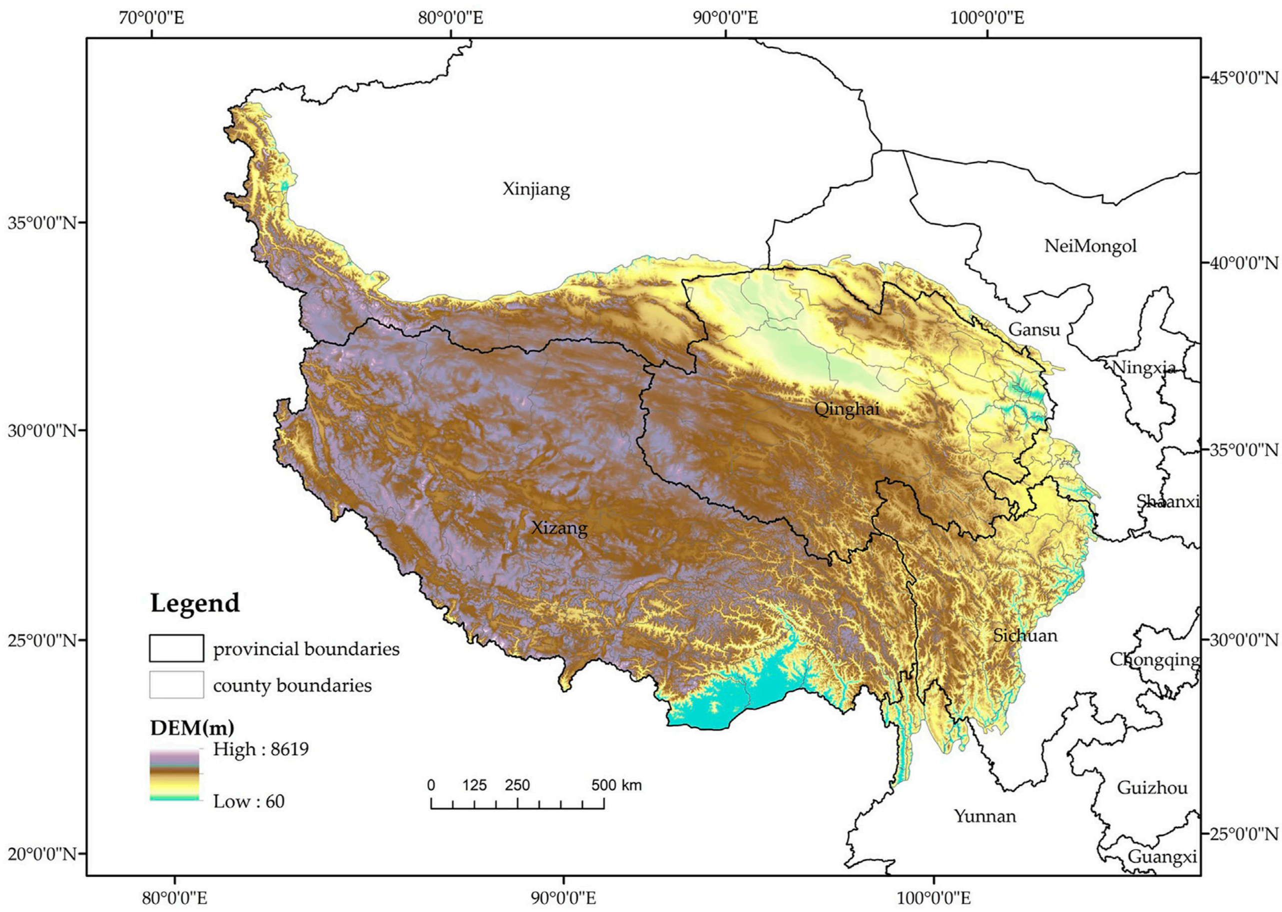


FIGURE 1
Overview of the study area.

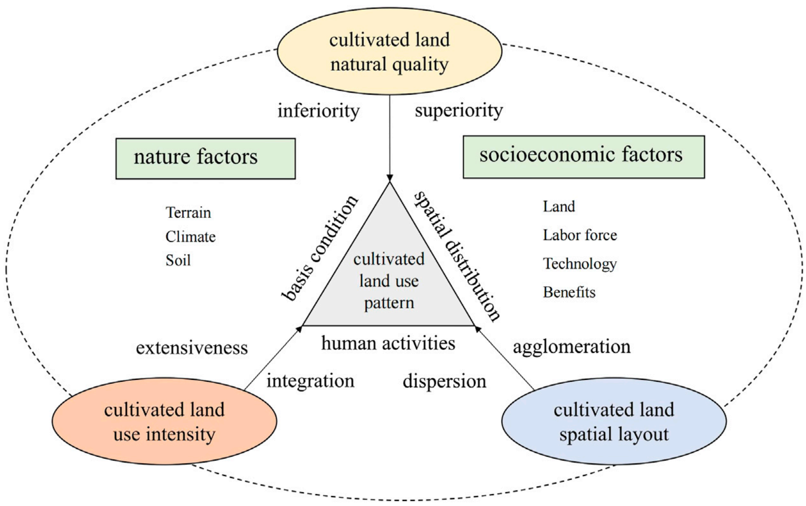


FIGURE 2
Research framework of cultivated land use pattern.

protection, increase agricultural income, and achieve sustainable economic, social and ecological goals for agricultural development.

3.2 Research methods

3.2.1 Evaluation system of cultivated land use pattern

3.2.1.1 evaluation model of the natural quality of cultivated land

The niche model is a theoretical method used to estimate species distributions in ecology. Existing studies have extended the application of niche models to the field of geography to study the matching degree between regional resource space and the resource demand of regional development. In this paper, referring to previous research results (Xiao and Ou, 2022), based on the niche model, the natural quality of cultivated land and the natural environment correspond to regional development and resource space, and a natural quality evaluation model of cultivated land is established. The evaluation factors are divided into three categories:

Positive factor: the higher the value, the higher the natural quality of cultivated land. There are upper and lower limits. The evaluation model is:

$$U_i = \begin{cases} 0 & X_i \leq A_{imin} \\ X_i / A_{ideal} & A_{imin} \leq X_i \leq A_{ideal} \\ 1 & X_i \geq A_{ideal} \end{cases} \quad (1)$$

Negative factor: the lower the value, the higher the natural quality of cultivated land. The evaluation model is:

$$U_i = \begin{cases} 1 & X_i \leq A_{imin} \\ 1 - \dfrac{X_i - A_{imin}}{A_{imax} - A_{imin}} & A_{imin} \leq X_i \leq A_{imax} \\ 0 & X_i \geq A_{imax} \end{cases} \quad (2)$$

Intermediate factor: The closer the solution is to the ideal value in a certain interval, the higher the natural quality of cultivated land. The evaluation model is:

$$U_i = \begin{cases} 0 & X_i \leq A_{imin}, X_i \geq A_{imax} \\ \dfrac{X_i - A_{imin}}{A_{ideal} - A_{imin}} & A_{imin} \leq X_i \leq A_{ideal} \\ \dfrac{A_{imax} - X_i}{A_{imax} - A_{ideal}} & A_{ideal} \leq X_i \geq A_{imax} \end{cases} \quad (3)$$

The evaluation results of the natural quality of cultivated land:

$$U = \left[\prod_{i=1}^{n} U_i\right]^{\frac{1}{n}} \quad (4)$$

In Formulas (1) ~ 4), U_i is the natural quality index of each category of evaluation factors i, X_i is the actual value of the evaluation factors i, A_{imin} is the lower limit value of the factor i, A_{imax} is the upper limit value of the factor, A_{ideal} is the ideal value of the factor, U i is the final evaluation result, and n is the number of evaluation factors.

Existing studies on the natural quality evaluation of cultivated land show that the natural conditions affecting the distribution and fertility of cultivated land include three categories: terrain, climate and soil (Xu et al., 2022). Soil is a prerequisite for farming and a necessary means of production. Soil organic matter content, pH and soil thickness affect soil texture; air temperature and precipitation conditions provide a suitable growth environment for crops, and topography affects the redistribution of surface water and heat conditions. Therefore, this study selects terrain factors (altitude, slope), climate factors (annual average temperature, average annual precipitation), and soil factors (soil pH, organic carbon content, soil layer thickness) to evaluate and classify the natural quality of cultivated land. Considering the suitability of the growth conditions of the four major crops of the Qinghai-Tibet Plateau, barley, wheat, pea, and rape, the thresholds of the evaluation factors were comprehensively determined (Table 1).

3.2.1.2 cultivated land spatial layout index

The landscape pattern index can condense landscape information, quantitatively reflect landscape structure composition and spatial configuration and is widely used in large-scale spatial layout research. Due to the strong correlation between many landscape pattern indices, the study refers to the results obtained by Ju et al. (2020), who conducted a correlation test and screening study on the spatial layout of land use and selected three landscape indices, namely, patch density, area weighted average nearest neighbor index, and area weighted patch nearest distance, to characterize the spatial layout of cultivated land. The patch density can reflect the intensity of patches, the area weighted average nearest neighbor index can measure the proximity of patches of the same type, and the area weighted patch nearest distance can reflect the dispersion or aggregation of patches of the same type. These three landscape pattern indices can reflect the aggregation and dispersion of patches in the landscape, but the calculation results are quite different. Therefore, a comprehensive index of cultivated land spatial layout was constructed, which can accurately reflect the aggregation and dispersion of cultivated land spatial layout by integrating the characteristics of the three indices. The formula for calculating the comprehensive index of cultivated land spatial layout is:

$$ICIS = (1 - P)\ln(RE) \quad (5)$$

In the formula, $ICIS$ is the cropland spatial layout index; the larger the value is, the more scattered the landscape pattern is, and the smaller the value is, the more scattered the landscape pattern is. P is the patch density, R is the area-weighted average nearest neighbor index, and E is the area-weighted patch closest distance.

3.2.1.3 Evaluation of cultivated land use intensity

Cultivated land use intensity is an important way to measure the impact of human activities on cultivated land. Existing studies have carried out research on the characterization of cultivated land use intensity from multiple perspectives, such as planting, input–output, intensification, and land use timing. Compared with the previous research results (Niu et al., 2019), the input–output perspective is more suitable for the study of cultivated land use intensity in space, the variables involved are more comprehensive, and the results are more in line with the actual situation. This paper constructs the index system of cultivated land use intensity according to the logic of input–output and following the principles of scientificity, rationality

TABLE 1 Natural quality classification of cultivated land.

		Ideal value	Limitation value	Index types
Topographic factors	Elevation/m (X_1)	≤2,500	≥4,500	Negative
	Gradient/°(x_2)	≤10	≥30	Negative
climatic factors	average annual temperature/°C (X_3)	15	<3	positive
	average annual precipitation/mm (X_4)	≥400	<100	positive
soil factors	soil PH (X_5)	6–7.9	<4/>9	intermediate
	soil organic carbon/g/kg (X_6)	≥40	<5	positive
	soil thickness/cm (X_7)	≥75	<20	xpositive

TABLE 2 Cultivated land use intensity evaluation index system.

Index	Variable	Variable declaration	Variable weight
input variables	technique	total power of agricultural machinery	0.202
	manpower	number of rural employees	0.187
	fertilizer	chemical fertilizer consumption	0.207
	land	sown area of crops	0.015
output variables	economic benefit	total value of farm product	0.186
	social benefit	total grain output	0.203

and availability of evaluation indicators. The input indicators reflect the amount of capital, labor and other production factors invested in the unit cultivated land area in the agricultural production process. In combination with previous research results, and taking into account the agricultural development situation and the availability of data in the Qinghai-Tibet Plateau region, four indicators were selected from the four aspects of technology, labor, fertilizer and land, including the total power of agricultural machinery, the number of rural employees, chemical fertilizer consumption, and sown area of crops. Output index refers to the social and economic benefits brought by certain input and utilization of cultivated land. Two indicators of total value of farm product and total grain output were selected. The entropy weight method was used to calculate the weight, and the evaluation index system of cultivated land use intensity was obtained as shown in Table 2.

3.2.2 Pattern recognition method of cultivated land use

In the form of a three-dimensional model, a recognition method of "natural quality-utilization intensity-spatial layout" of cultivated land use features was constructed as the theoretical basis for the classification of cultivated land use types. As shown in Figure 3, the natural quality, utilization intensity and spatial layout of cultivated land are taken as the *X*, *Y*, and *Z* axes respectively, the three indicators are divided into three grades from low to high according to the threshold value of the calculation results. According to the different forms and characteristics of cultivated land use in the study area, it is divided into four types of cultivated land use.

The study divides the counties whose utilization intensity and spatial layout are both grades II and III as High efficiency-Scale utilization pattern; the natural quality and spatial layout are classified as II and III grades, and the utilization intensity is grade I as Potential-Composite utilization pattern; The natural quality and utilization intensity of grades II and III, and the spatial layout of grade I are classified as Dispersion-Stereoscopic utilization pattern; those with at least two dimensions of natural quality, utilization intensity and spatial layout of grade I are classified as Low efficiency-Ecology utilization pattern.

4 Results

4.1 Characteristics of cultivated land use from different perspectives

4.1.1 Natural quality of cultivated land

The topography, climate, and soil natural quality of cultivated land in the study area were calculated, and the natural quality distribution interval of 0–1 was obtained. As shown in Figure 4, topographic and climatic factors greatly limit the natural quality of cultivated land. Mainly due to altitude restrictions, the high-altitude areas in the west were not suitable for crop growth. The southeastern part of the plateau is low in altitude, but the terrain fluctuates greatly, and the slope also has a certain restrictive effect on crop growth. From the climate evaluation results, more than 70% of the region does not provide enough natural precipitation and heat. The harsh natural conditions in the plateau and frigid regions with low

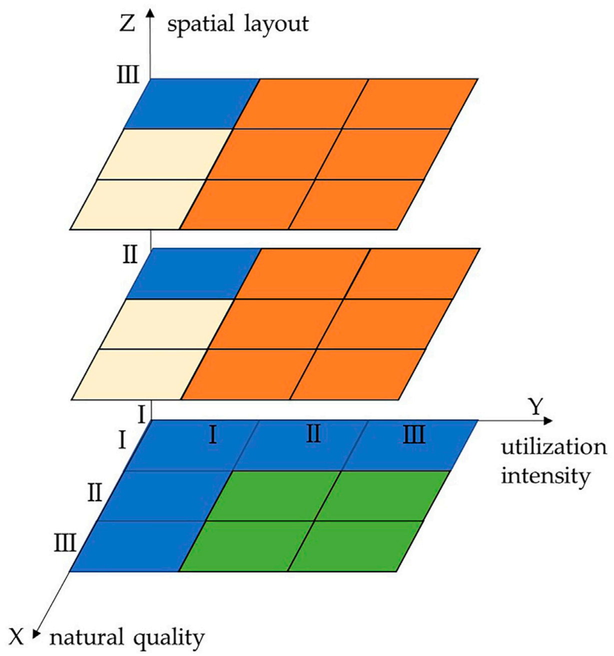


FIGURE 3
Recognition process of cultivated and use pattern.

temperature and low rainfall limit crop planting, and the remaining areas were concentrated between 0.316 and 0.5 and 0.707–0.866. The rivers and mountains in southern Tibet, Sichuan, and Yunnan are widely distributed, the altitude is low, and the natural precipitation and sunlight are relatively sufficient, which can provide natural growth conditions. The soil is less restrictive to crop planting on the Qinghai-Tibet Plateau, and the low-value areas are mainly distributed around the Qaidam Basin because the soil types are mostly salinized desert soil and gypsum desert soil, and the land is barren and has low organic matter content.

Combined with the three factors of terrain, climate, and soil, the evaluation results of the natural background quality of cultivated land were finally determined. The averaged results were divided into three categories: low, medium and high according to the classification criteria of 0–0.029, 0.029–0.299, and 0.299–0.628, respectively. Low-quality, medium-quality, and high-quality counties cover a similar number of counties, but most of the cultivated land is distributed in medium- and high-quality areas, and the evaluation results are consistent with the actual situation (Figure 4).

4.1.2 Spatial layout of cultivated land

Combining the three landscape pattern indicators, the distribution of cultivated land in the counties of the Qinghai-Tibet Plateau was obtained (Table 3). The degree of arable land agglomeration has a strong correlation with the size of the area. The high agglomeration types are mainly distributed in the Hung River valley and the Qaidam Basin in Qinghai and Xigaze and Shannan in Tibet. They are the main agricultural development areas on the Qinghai-Tibet Plateau and can provide good agricultural production conditions. Most of the medium agglomeration types exist between valleys due to topographical constraints and are mostly distributed in strips, with strong connectivity and weak aggregation. The low aggregation type mainly exists in the border zone of Ganzi Tibetan Autonomous Prefecture in Sichuan, Tibet, Qinghai, Yunnan, Gansu and the plateau Frontier zone. The cultivated land area is small and scattered, which is not suitable for the development of large-scale agriculture and involves the least cultivated land area (Figure 5).

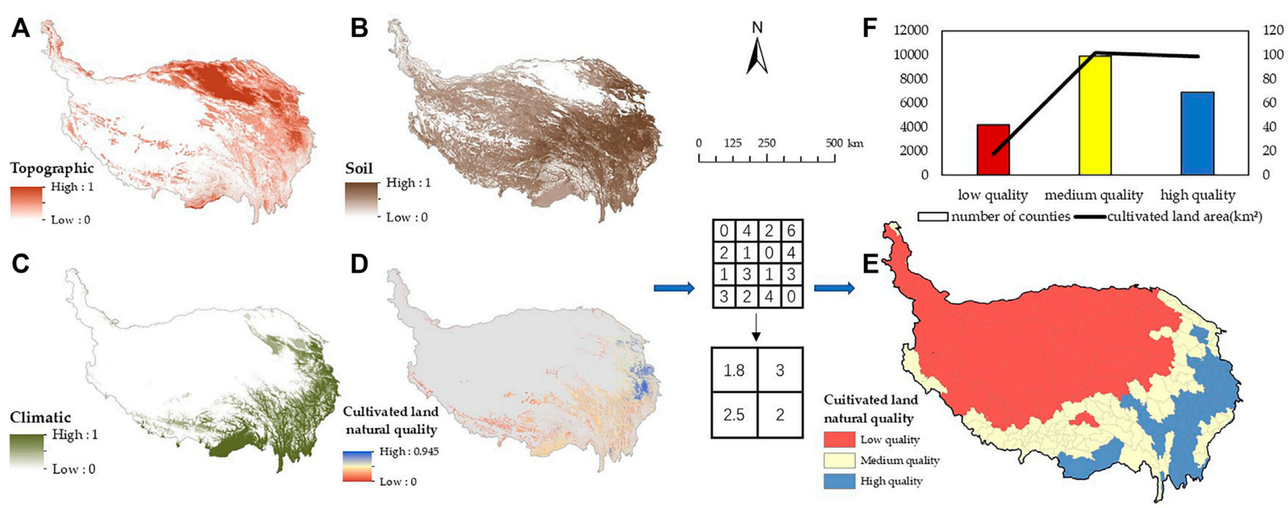
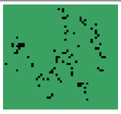
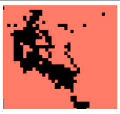


FIGURE 4
The division process and results of the natural background quality of cultivated land at the county scale on the Qinghai-Tibet Plateau is: **(A)** the result of terrain factor evaluation; **(B)** the result of soil factor evaluation; **(C)** the assessment result of climate factors; **(D)** the result of comprehensive evaluation; **(E)** the result of the processed county scale evaluation; and **(F)** the number of counties and cultivated land area involved under different natural quality levels.

TABLE 3 Types and characteristics of the spatial layout of cultivated land at the county scale on the Qinghai-Tibet Plateau.

Spatial layout types	Examples	Features	Number of counties	Cultivated land area (km^2)
Low agglomeration		Cultivated land scattered, basically no dominant patch, weak connectivity, fuzzy boundary	52	323
Medium agglomeration		Cultivated land is mostly banded distribution, the aggregation is weak, the dominant patch is not obvious, the boundary is clear	59	669
High agglomeration		Cultivated land is contiguous, aggregated distribution, obvious advantage patch, clear boundary	40	1,188

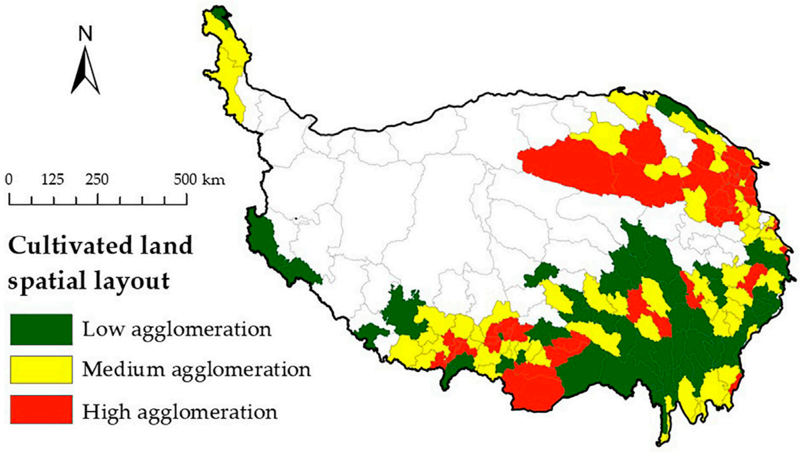


FIGURE 5
Spatial layout of cultivated land at the county scale on the Qinghai-Tibet Plateau.

4.1.3 Cultivated land use intensity

Figure 6 shows the calculation results and spatial distribution of cultivated land use intensity. The range of cultivated land use efficiency results on the Qinghai-Tibet Plateau is 0.010–0.019. According to the natural discontinuous point method, the calculation results of cultivated land use intensity are divided into three intensity levels: low, medium, and high. Among them, the high-intensity utilization of cultivated land involves the largest area of cultivated land, mainly concentrated in the Hung River valley of Qinghai and its surrounding counties. The Hung River valley is rich in labor resources and advanced agricultural technology, and the government vigorously supports the development of modern new agriculture, which is the main agricultural area in Qinghai Province. The number of counties involved in medium-intensity utilization is the largest, mainly distributed at the junction of Sichuan, Yunnan, Qinghai and Tibet, and the input is at a low level. The lack of labor and the scattered distribution of cultivated land limit the utilization of cultivated land. The counties with low cultivated land use intensity are distributed in the “One-River-Two-Tributaries” basin, Changdu, Linzhi area in Tibet, and the western edge of the plateau. Although these areas are the main agricultural planting areas in Tibet, their productivity and agricultural technology promotion are backwards, and the overall use intensity is low.

4.2 Recognition results of cultivated land use patterns

The classification results of cultivated land use pattern recognition according to the three-dimensional mode can be seen (Table 4; Figure 7):

High efficiency-Scale utilization pattern area involved a total of 64 counties, with a cultivated land area of 12,428 km^2 (57.02%), mainly distributed in the Hung River valley of Qinghai, Sichuan, and

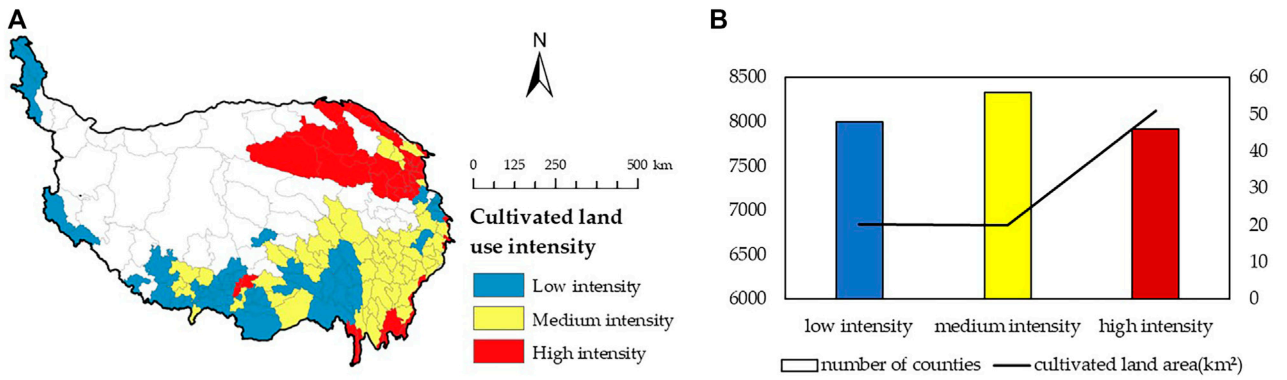


FIGURE 6
Spatial distribution of cultivated land use intensity evaluation results **(A)**; number of counties and cultivated land area included in different grades of cultivated land use intensity **(B)**.

TABLE 4 Recognition results of cultivated land use patterns.

Cultivated land use pattern types	The combination of ' natural quality-utilization intensity-spatial layout '	Number of counties	Cultivated land area (km^2)	Pattern feature
High efficiency -Scale type	I-II-III、I-III-II、II-II-III、II-II-II、II-III-III、II-III-II、III-III-II、III-II-II	64	1,243	Cultivated land use intensity is high, cultivated land is distributed in large areas, human dominance is strong, the main development of large-scale agriculture
Potential-Composite type	II-I-II、II-I-III、III-I-II、III-I-III	32	605	Cultivated land use intensity is low, the natural quality is high, the spatial layout is more concentrated, can be used as agricultural development resources reserve area
Dispersion-Stereoscopic type	II-II-I、II-III-I、III-II-I、III-III-I	35	242	Cultivated land is more dispersed, natural quality is better, the use of high intensity, the main development of three-dimensional agriculture
Low efficiency -Ecology type	I-I-I、I-II-I、I-I-II、I-I-III、II-I-I、III-I-I	19	90	Cultivated land use intensity is low, the natural quality is poor, the spatial layout is basically decentralized, in the state of returning farmland or fallow

the southern edge of Yunnan. The cultivated land use intensity was medium and high intensity, and the spatial layout also had a high degree of concentration, mostly professional production of large-scale crop cultivation and a high level of agriculture. With the exception of a few counties in Qinghai and Tibet that are on the fringe of cultivated land distribution, more than 90% of the counties have high natural quality cultivated land, which provides a prerequisite for the large-scale utilization of cultivated land. This pattern utilizes natural and economic advantages to increase the input of agricultural production factors, improve infrastructure conditions, improve grain output efficiency, broaden agricultural development channels, and give full play to agricultural economic benefits. It is a key area for modern agricultural development on the Qinghai-Tibet Plateau.

Potential-Composite utilization pattern area consists of 32 counties, with a cultivated land area of 6,044 km^2 (27.73%), which is concentrated in the area of the "One-River-Two-Tributaries" basin in Tibet. The nearly closed ecological environment has formed unique natural conditions in the area of the One-River-Two-Tributaries basin. It is rich in water resources, suitable for climate resources, concentrated land and easy to cultivate. The natural quality of cultivated land in this pattern is medium to high grade, and the spatial distribution of cultivated land is relatively concentrated, but the use intensity of cultivated land is not high, and the potential of cultivated land use is large. The counties

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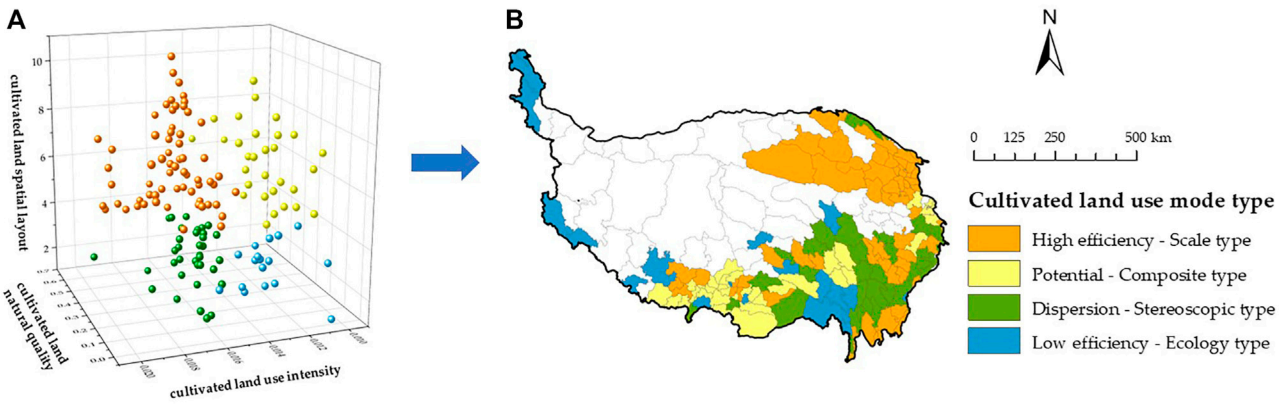

FIGURE 7
Three-dimensional ensemble results of cultivated land use pattern **(A)**; Spatial distribution results of cultivated land use pattern **(B)**.

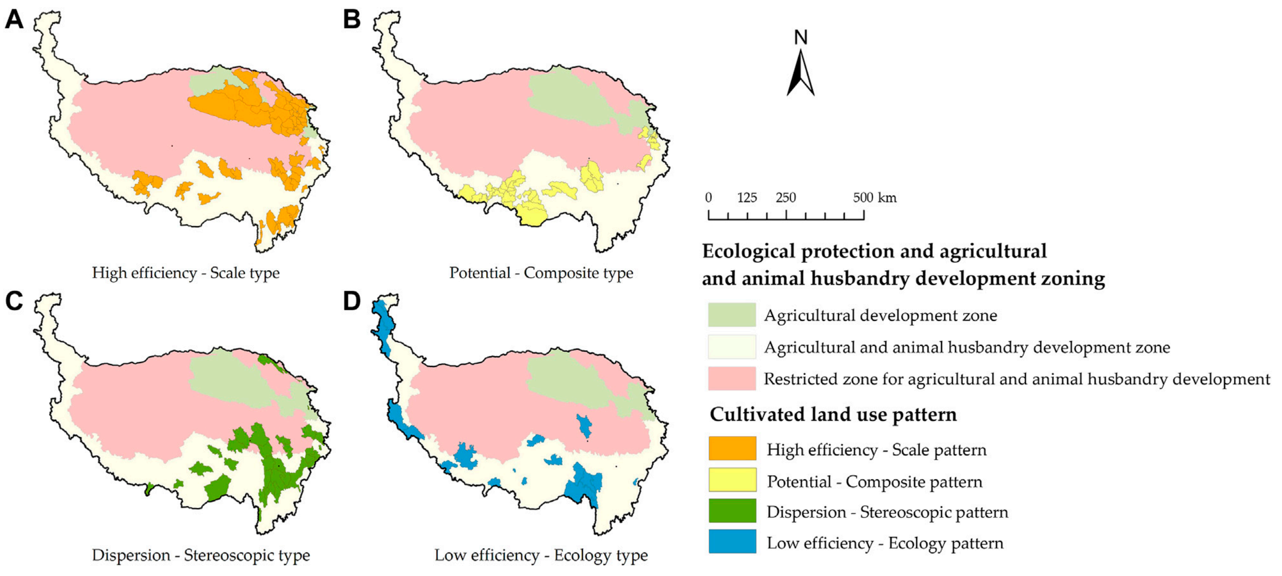

FIGURE 8
Optimized zoning of cultivated land use patterns on the Qinghai-Tibet Plateau: **(A)** High efficiency-Scale type; **(B)** Potential-Composite type; **(C)** Dispersion-Stereoscopic type; **(D)** Low efficiency-Ecology type.

around Shigatse develop industrialized and business-oriented agriculture, and the counties around Lhasa and Shannan in the Tibet Autonomous Region have developed animal husbandry. Relying on their own natural, economic and regional advantages, they have established a variety of complex, circular and ecological agricultural development modes. The region makes full use of its own conditions to develop suitable agriculture according to local conditions and builds a plateau with a characteristic agricultural development base.

Dispersion-Stereoscopic utilization pattern involves 35 counties, with an area of 2,423 km^2 (11.12%) of arable land. It is basically located in the Hengduan Mountains and its surrounding areas. The terrain is undulating, the mountain is high, the valley is deep, the climate difference is large, and the vertical differentiation is significant. The natural quality and utilization intensity of cultivated land in this pattern are generally high, and the spatial distribution is too scattered, which is not suitable for the development of large-scale agriculture. However, it has obvious geographical advantages and is suitable for the development of three-dimensional agriculture. For example, the ganzi tibetan autonomous prefecture of Sichuan Province relies on its own industrial advantages to create "special, refined and excellent" rural characteristic agriculture, establish a characteristic agriculture and forestry industry base, and promote the development of plateau characteristic agriculture.

Low efficiency-Ecology utilization pattern area includes a total of 19 counties, involving the least cultivated land area, accounting for only 902 km^2 (4.14%), scattered in the southern edge of Xinjiang, the southern

TABLE 5 Number of counties and cultivated land area in optimized subregions of cultivated land use pattern.

		Agricultural development zone	Agricultural and animal husbandry development zone	Restricted zone for agricultural and animal husbandry development
High efficiency-Scale type	Cultivated land area	594.92	381.73	266.48
	Proportion of cultivated land area	47.86%	30.71%	21.44%
Potential-Composite type	Cultivated land area	18.80	527.23	59.36
	Proportion of cultivated land area	3.11%	87.09%	9.81%
Dispersion-Stereoscopic type	Cultivated land area	0.34	161.38	80.29
	Proportion of cultivated land area	0.14%	66.68%	33.18%
Low efficiency-Ecology type	Cultivated land area	0.00	78.41	11.59
	Proportion of cultivated land area	0.00%	87.12%	12.88%

border of the plateau and the central plateau of the plateau and is not the main area of agricultural development. The scale of cultivated land is small, the location is remote, and the cost of cultivation is high. The natural quality, spatial layout and utilization intensity of cultivated land in this pattern are basically at a low level, and the basic conditions for agricultural development are relatively poor. In recent years, the protection and construction of cultivated land basic farmland in the Qinghai-Tibet Plateau has been strengthened, and the areas unsuitable for cultivated land development have gradually clarified the development direction and ensured ecological priority development.

4.3 Optimization of cultivated land use pattern

Referring to the results of ecological protection and agricultural and animal husbandry development regionalization of the Qinghai-Tibet Plateau divided by Lu Changhe (Lv and Liu, 2020) and others, this paper combines the existing research contents and needs and divides the Qinghai-Tibet Plateau into three regions according to the overall development direction: agricultural development area, agricultural and animal husbandry development area and agricultural and animal husbandry development limited control area. As shown in Figure 8 and Table 5, the three major development zones of the Qinghai-Tibet Plateau and the identification results of cultivated land use are compared, and optimization suggestions are proposed for the existing cultivated land use pattern.

Approximately 80% of the counties in the High efficiency-Scale utilization pattern are located in agricultural development areas and agricultural and animal husbandry development areas, and a small number of counties around the Hung River valley, such as Qilian County and Gangcha County, are in the restricted area for agricultural and animal husbandry development. The use of cultivated land in the main production areas should be strictly controlled, and ecological protection should be prioritized. In addition, Seda County, Ganzi County in Sichuan, etc., are located in the critical region, and the scope of cultivated land expansion should also be strictly limited. Approximately 87% of the counties in the Potential-Composite utilization pattern are in the agricultural and animal husbandry development area, 3% are in the agricultural development area, and 10% are in the development restricted area. The county and Xiahe County should pay attention to coordination and ecological protection while flexibly optimizing the agricultural development pattern.

Approximately 67% of the counties in the Dispersion-Stereoscopic utilization pattern are in the agricultural and animal husbandry development zone, and nearly 33% of the counties are in the restricted and controlled agricultural and animal husbandry development zone, including Sunan County, Gansu Province, Yushu County, and Nangqian County in Qinghai Province. Banma County, Rangtang County, Shiqu County and Dege County in Sichuan Province have expanding cultivated land, and most of them are newly added cultivated land. The expansion of cultivated land does not consider whether it will affect the habitat of wild animals, and water conservation and protection areas have caused certain conflicts between agricultural development and ecological protection. The Low efficiency-Ecology utilization patterns are all distributed in the agricultural and animal husbandry development areas and restricted control areas; the county of the agricultural and animal husbandry development area accounts for approximately 85%, and the county of the agricultural and animal husbandry restricted control area accounts for approximately 15%. The natural and spatial distribution conditions of cultivated land in Chengduo County in the restricted control area are not suitable for agricultural development, and the existing pattern should be maintained to reduce the use of cultivated land.

5 Discussion

5.1 Reasons for the formation of cultivated land use patterns in different regions of the Qinghai-Tibet Plateau

The Qinghai-Tibet Plateau has a vast territory, with large differences in natural endowment and population density among regions (Gao et al., 2021) and different development goals and

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priorities. Therefore, there are certain differences in the use of cultivated land in different regions. Due to the limitations of altitude, soil and climate factors, the cultivated land on the Qinghai-Tibet Plateau is mainly distributed in the Hung River valley area, the Yarlung Zangbo River Valley and the southeast edge of the plateau. In addition, the influence of the labor force, agricultural production technology and other factors determines the distribution range of the main agricultural production areas on the Qinghai-Tibet Plateau. In addition, the mountain vertical belt in the southeast of the Qinghai-Tibet Plateau, formed by natural conditions, has a low altitude and good light and temperature conditions. The distribution of alpine shrubs and meadows is suitable for grazing. The mountain forest belt in the middle provides people with wood, fuel, etc., showing typical mountain land three-dimensional utilization characteristics. In addition to natural conditions, national policies also affect the use of cultivated land on the Qinghai-Tibet Plateau. The Ecological Protection Law of the Qinghai-Tibet Plateau (Draft) proposes to strictly take ecological protection as the prerequisite and forcibly return farmland in some high-altitude or low-temperature areas, which also makes some areas in Tibet unsuitable for efficient and large-scale use of cultivated land. Many factors, such as nature, human activities and national policies, have formed the current situation of cultivated land use differentiation in the Qinghai-Tibet Plateau.

5.2 Rationality of optimizing the utilization of existing cultivated land in the Qinghai-Tibet Plateau by dividing agriculture and animal husbandry development zones

The research results show that since 2002, the planting structure of the Qinghai-Tibet Plateau has undergone a major transition, gradually reducing the sowing of food crops and increasing the proportion of cash crops (Liu et al., 2016). With the growth of the population and the continuous improvement of productivity, agriculture and animal husbandry have developed rapidly, and the scale and intensity of cultivated land use have increased. Most regions have a strong dependence on cultivated land resources, and cultivated land use shows strong regional differences (Liu et al., 2021). Since the 18th National Congress of the Communist Party of China, the state has attached great importance to the ecological protection of the Qinghai-Tibet Plateau, strengthened the systematic protection and risk prevention of the Qinghai-Tibet Plateau, and made ecological protection a prerequisite for regional development (Fan and Fang, 2022). Therefore, to maintain the sustainable use of cultivated land in the Qinghai-Tibet Plateau, it is necessary to arrange agricultural production according to the development goals of different regions and local conditions. The ecological protection and agricultural and animal husbandry regulation zoning of the Qinghai-Tibet Plateau proposed by Lv Changhe et al. has taken into account the terrain (elevation, slope), vegetation types and coverage, land use status and agricultural use types, distribution of nature reserves, ecological protection priorities and agricultural development directions. The zoning results have been applied to a number of studies related to the ecological security protection of the Qinghai-Tibet Plateau, with strong practical significance. They can be used as a basis to judge whether the cultivated land use in the Qinghai-Tibet Plateau is reasonable at the county level.

5.3 Whether optimized cultivated land utilization meets the needs of agricultural production and ecological protection

The cultivated land use pattern and ecological protection of most counties in the Qinghai-Tibet Plateau are consistent with the agricultural and animal husbandry development zoning. However, there is still a conflict between agricultural development and ecological protection in the agricultural development area, the agricultural and animal husbandry development area and the agricultural and animal husbandry development restricted area. Thus, the phenomenon of occupying the resources in the restricted area needs to be adjusted. For counties at the critical point of zoning, it is recommended to give priority to the development of high-quality cultivated land and unused land within the region, activate idle cultivated land within the region, and prohibit the spread of new cultivated land to the surrounding restricted areas. The counties located in the restricted areas should continue to implement the project of returning farmland to forests, implement the responsibility system of local governments for farmland protection objectives. By optimizing and adjusting the utilization of existing cultivated land in the Qinghai-Tibet Plateau, focusing on the use of high-quality cultivated land resources, reducing unreasonable development and utilization, and effectively alleviating the contradiction between agricultural production and ecological protection in various regions. In addition, the optimization of cultivated land use can also reasonably allocate water resources supply to a certain extent, reduce agricultural non-point source pollution caused by large-scale use of chemical fertilizers and pesticides, improve soil quality, alleviate soil erosion caused by large-scale reclamation of cultivated land, follow the boundary of nature reserves, and protect the biodiversity of the Qinghai-Tibet Plateau.

6 Conclusion

The Qinghai-Tibet Plateau is an important ecological barrier area in China. In order to achieve the goal of sustainable use of cultivated land, the use of cultivated land in this area needs to strictly follow the principle of giving priority to ecological environment protection. This paper constructs an analysis framework of cultivated land use patterns based on the three-dimensional model of natural quality-utilization intensity-spatial layout (NUS). On this basis, the types of cultivated land use patterns in the study area was identified, and the optimization direction of cultivated land use patterns at the county scale in the Qinghai-Tibet Plateau was proposed based on the ecological protection and agricultural and animal husbandry development division of the Qinghai-Tibet Plateau. The main conclusions are as follows:

There are four different patterns of cultivated land use in the Qinghai-Tibet Plateau. High efficiency-Scale utilization pattern of cultivated land use intensity is high, the spatial distribution of cultivated land is agglomerated, and large-scale agriculture is mainly developed; Potential-Composite utilization pattern of cultivated land use intensity is low, but the natural quality is high, and the spatial layout is relatively concentrated, which can be used as a reserve area for agricultural development resources; Dispersion-Stereoscopic utilization pattern of cultivated land is relatively scattered, with high natural quality and high utilization intensity, and the three-dimensional agriculture is mainly developed; Low efficiency-Ecology utilization pattern of cultivated land has low utilization intensity, poor natural quality, and the spatial layout is basically decentralized. In a state of abandonment or fallow.

Comparing the results of the development zoning of the Qinghai-Tibet Plateau, all four types of cultivated land use patterns are in the restricted area of agricultural and animal husbandry development. Counties with High efficiency-scale, Potential-composite, and Dispersion-stereoscopic utilization patterns located at the borders of agricultural and animal husbandry development control areas should strictly limit the scale of cultivated land and coordinate the relationship between agricultural and animal husbandry development and ecological protection. Counties with Low efficiency-Ecology patterns should continue to maintain the existing state of utilization and put the restoration of the ecology first.

According to the research results, in order to realize the sustainable utilization of cultivated land in the Qinghai-Tibet Plateau in the future, we should first implement a strict ecological environment protection system, determine the use of major natural resources such as water, cultivated land, grassland and forest, set the bottom line of environmental protection such as the use of chemical fertilizers and pesticides, the total amount of water and gas pollution emissions, establish and improve the regional red line management system, strictly control the new land use, and revitalize the stock land. Secondly, it is necessary to develop plateau characteristic industries according to local conditions, build an eastern and southeastern plateau characteristic ecological agricultural belt with the One-River-Two-Tributaries basin and the Hung River valley area as the main body, and vigorously develop plateau characteristic ecological animal husbandry in the Sanjiangyuan Regin, western and northern Tibet. It emphasizes the combination of agriculture and animal husbandry, accelerates the industrialization of agriculture and animal husbandry, promotes the comprehensive development of various agricultural and animal husbandry methods, attaches importance to the role of ecological agriculture in promoting agricultural and animal husbandry development and ecological environment protection, and gradually realizes the virtuous cycle of agricultural and animal husbandry economic development and ecological environment protection.

Data availability statement

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

Author contributions

Conceptualization, methodology, visualization and writing—original draft preparation, XW; investigation, resources, CP; writing—review and editing, supervision, project administration, DZ and GJ. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by the Second Tibetan Plateau Scientific Expedition and Research Program, Grant No.2019QZKK0405.

Acknowledgments

We are also grateful for the comments and criticisms of the journal's reviewers and our colleagues.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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TYPE Original Research
PUBLISHED 10 March 2023
DOI 10.3389/fenvs.2023.1130234

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Land Use Dynamics, a section of the journal Frontiers in Environmental Science

RECEIVED 23 December 2022
ACCEPTED 01 March 2023
PUBLISHED 10 March 2023

CITATION
Liang Y and Geng B (2023), Effects of paddy field non-grainization consolidation on sustainable eco-functions protection of soil bacterial: Empirical evidence from Zhejiang province, China.
Front. Environ. Sci. 11:1130234.
doi: 10.3389/fenvs.2023.1130234

Effects of paddy field non-grainization consolidation on sustainable eco-functions protection of soil bacterial: Empirical evidence from Zhejiang province, China

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The increasing "non-grainization" of paddy fields affecting large-scale grain cultivation and impacting the sustainable eco-functions protection of soil bacterial in China. The same problem of "non-grainization" has threatened food security and farmland soil ecological functions in other areas of the world. Although previous research has demonstrated that soil microorganisms are strongly affected by land use change, little is known about the effects of paddy field non-grainization consolidation (NGC) on soil microorganisms. This study examined soil samples before and after paddy field NGC in Zhejiang province, China, measured soil environmental factors and performed 16S rDNA amplicon sequencing to analyze the changes in soilbacterial communities and ecosystem functions before and after NGC. Results show that NGC increased the relative abundances of Proteobacteria (27.89%) and Actinobacteria (25.25%) in the project zones. Total soil bacteria increased in all samples after NGC implementation in terms of absolute soil bacterial community content, but there were large differences. NGC improved the alpha diversity indices, including Ace, Chao1, Coverage, and Shannon indices ($p < 0.01$) in terms of soil bacterial community diversity. The data analysis of RDA and the significance test showed that the environmental factors which were close-knitted with the soil bacterial diversity and structure of the sample sites were TN, AP, pH, SOM, FIQ, and AK. Wilcoxon rank sum test results showed that NGC also significantly enhanced the amino acid transport and metabolic functions of soil bacterial. Our findings suggest that NGC is beneficial to improve the paddy field soil bacterial diversity, enhance the versatility of soil ecosystems, and promote sustainable arable land soil ecosystem protection. The quantitative results would be useful for better studying the use of land remediation engineering measures to the remediation and maintenance of bacterial diversity and sustainable eco-functions protection in paddy fields.

KEYWORDS

non-grainization, soil bacterial communities, ecosystem functions, 16S rDNA amplicon sequencing technology, paddy fields

Introduction

The term "non-grain production of arable land" refers to the conversion of arable land originally used for grain crop production into cash crops or even agricultural production such as pond farming and livestock breeding (Zhang et al., 2023). As arable land serves as an important basic resource to ensure national food security, the excessive non-grain production will seriously affect food production and thereby national food security to certain extent (Lu et al., 2021). High-quality arable land resources equipped with food production and ecological functions, paddy fields are valued by the Chinese central government. However, factors such as low farmer income from grain production and the structural adjustment of the agricultural sector have resulted in the increasing "non-grainization" of paddy fields, affecting large-scale grain cultivation and impacting the sustainable eco-functions protection of soil bacterial (Su et al., 2020; Guo and Wang, 2021). In 2020, the General Office of the State Council of China successively issued the "Notice on Resolutely Stopping the "Non-Agriculturalization" of Arable Land" and "Opinions on Preventing the Non-Grainization of Arable Land and Stabilizing Grain Production." In addition, the local governments of southern China have been actively carrying out land consolidation against the non-grainization of paddy fields. Engineering measures, such as consolidating non-grain paddy fields, restoring grain production functions, and improving the quality of arable land, have been implemented in project zones, seeking to improve the parcel shape, parcel size, and ecological landscape indices of paddy fields, thereby significantly increasing the scale of grain cultivation and effectively resolving issues with the non-grainization and fragmentation of paddy fields (Shi et al., 2018).

Soil bacteria are an indispensable component of the soil ecosystem and are involved in various soil physical and biochemical processes, including the decomposition of soil organic matter (SOM), the formation of humus, and the transformation and circulation of nutrients. Thus, the quality and health of soil ecosystems are closely linked with the changes in the community structure of soil bacteria (Bitas et al., 2013; Lozano et al., 2014; He et al., 2020; Guo et al., 2021). According to existing studies, the different cultivation and utilization methods of arable land can alter their soil physicochemical properties, including pH, organic carbon, available potassium (AK), and moisture content, significantly impacting soil bacteria (Angel et al., 2010; Legrand et al., 2018). From the perspective of relative abundance (Lu et al., 2020), found that the implementation of land consolidation engineering led to improvements in soil heavy metal contamination while also enhancing the diversity and functionality of soil bacteria. Based on the indices of relative abundance obtained through high-throughput sequencing (Lin et al., 2019), demonstrated that land consolidation could improve SOM, pH, moisture content, and other physicochemical properties, thereby enhancing soil bacterial diversity. Conversely, other researchers have found empirical evidence indicating that land consolidation had a substantial impact on the community composition of soil bacteria, and the intensity of engineering measures disrupted and reduced soil ecosystem stability (Li et al., 2019). Thus, researchers have mainly focused on the crucial role of soil bacteria in arable land ecology and food production, arguing that the implementation of land consolidation engineering may have an impact on soil bacteria. However, little is known about the effects of large-scale non-grainization consolidation (NGC) on eco-functions of soil bacterial in the double- and single-cropping rice sub-regions in the middle and lower reaches of the Yangtze River (Jin and Zhong, 2022), key rice production regions with an immense impact on the trends of national grain output. High-throughput sequencing for the analysis of community structure allows the in-depth investigation of information on bacterial community structure. It greatly expands the information obtained on bacteria at the molecular level, further enhancing the acquisition of bacterial community structure information. Previous studies involving high-throughput sequencing experiments have concluded that land consolidation could optimize the soil bacterial communities in farmland (Lin et al., 2019). Nevertheless, employing high-throughput sequencing alone to study the community structure of soil bacteria only provides the species information and relative abundances of the community structure but not the absolute content index, which is one of the three key elements in the evaluation of ecosystem community structure (Lou et al., 2018; Yang et al., 2018; Jiang et al., 2019). Absolute content is a critical indicator for the evaluation of bacterial community structure, and its absence implies that the true quantities of bacterial communities cannot be accurately reflected (Chen et al., 2020). Therefore, we explored the influence mechanism of the effects of paddy field NGC on the soil bacterial diversity and its ecological function by innovatively combining of the relative abundance and absolute content indicators of soil bacteria. Which will have important theoretical and practical implications for sustainable eco-functions protection of soil bacterial in the study area (Yang et al., 2018).

In this study, soil samples were collected before and after paddy field NGC. Soil bacterial DNA was extracted from these samples, and 16S rDNA amplicon sequencing was performed to explore the effects of paddy field NGC on soil bacterial communities. It is hoped that our findings will provide basic data and supporting evidence for the sustainable eco-functions protection of soil bacterial for implementing the NGC of arable land.

Materials and methods

Profile of study area

Non-grain production of arable land, as a severe threat to food security, has attracted great attention in China and other countries of the world (Zhuang et al., 2022). China has been implementing the world's most strict cultivated land protection system to ensure staple food security, and has given priority to cultivated land for grain crops (Lu et al., 2021), but the problem of non-grain cultivation in China has become increasingly prominent, with the rate of "non-grain cultivation" of about 27% (Kong, 2020), which has threatened China's food security and sustainable agricultural development.

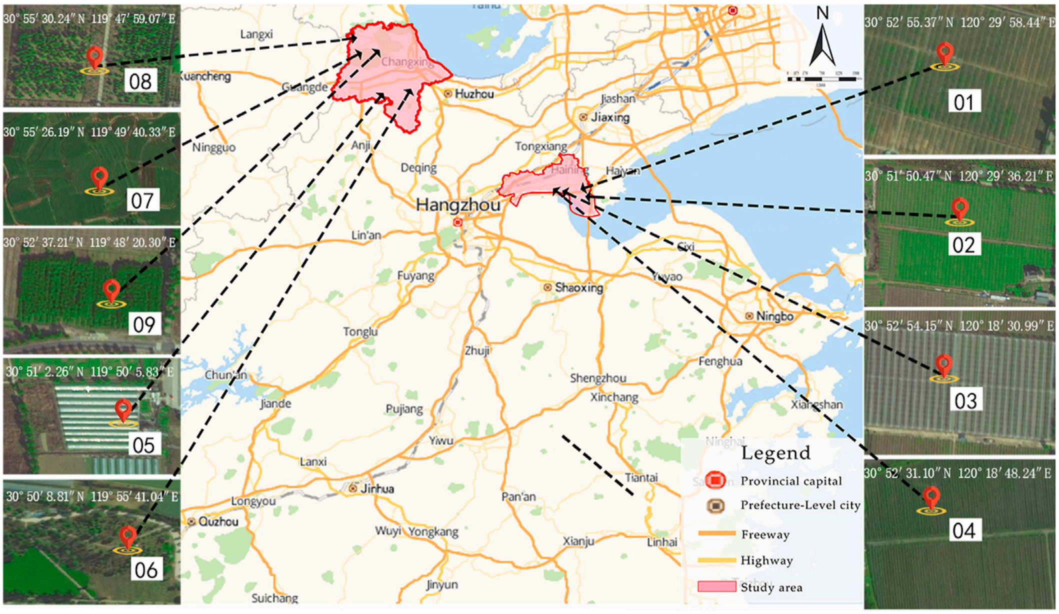

FIGURE 1
Schematic diagram of the study area and distribution of sampling points.

TABLE 1 Changes in arable land-use patterns before and after non-grainization consolidation in project zones Unit: ha.

Project zone no.	Location of soil sampling sites	Area of the plot	Crops	
			Before NGC	After NGC
01	Wanxin Village, Dingqiao Town	2.35	Watermelons	Rice
	Haining City, Jiaxing City			
02	Xincang Village, Dingqiao Town	3.81	Vegetables	Rice
	Haining City, Jiaxing City			
03	Shijing Village, Zhouwangmiao Town	4.61	Grapes	Rice
	Haining City, Jiaxing City			
04	Jingshan Village, Zhouwangmiao Town	2.54	Blueberries	Rice
	Haining City, Jiaxing City			
05	Xiaoxikou Village, Heping Town	2.08	Strawberries	Rice
	Changxing County, Huzhou City			
06	Hengshan Village, Heping Town	2.67	Pear trees	Rice
	Changxing County, Huzhou City			
07	Xiangyang Village, Lincheng Town	3.93	Tea	Rice
	Changxing County, Huzhou City			
08	Qiaonan Village, Lincheng Town	1.42	Mulberry trees	Rice
	Changxing County, Huzhou City			
09	Xinhua Village, Lincheng Town	1.33	Shrubs	Rice
	Changxing County, Huzhou City			

Note: Data from survey drawings of the project zones; NGC, Non-grainization consolidation.

Arable land is, by definition, a "living" organism whose health depends on the beneficial interactions between soil organisms, crops, and the environment in which soil organisms are an important part of the arable land ecosystem (Zhuang et al., 2022). As the research on arable land conservation progresses, more studies have paid closer heed to the possibility of repairing arable land biodiversity. Therefore, to tease out the characteristics of the impact of non-grainization consolidation on arable land soil bacterial communities and their ecological functions with the data from the typical high rice production area in China can provide a useful reference for the research on the conservation and repair of arable land biodiversity and the function as per sustainable utility of arable land. The northern Zhejiang plain, located in the northern part of Zhejiang Province, is a typical sub-region for double- and single-cropping rice in the middle and lower reaches of the Yangtze River. This region has accessible waterways and predominantly consists of loam paddy fields, with a history of rice cultivation that spans several millennia (Li et al., 2016). However, due to the large gap in the comparative income of rice cultivation, there has been a continuous increase in non-grain cultivation within the region, leading to the cross-distribution of grain-producting paddy fields with non-grain-producing arable land. This pattern of distribution is unsuitable for large-scale and mechanized rice production and has affected the utilization of paddy fields and the improvement of grain production capacity (Li et al. 2021b). Since 2020, under the leadership of the Zhejiang provincial government, the counties and cities in the northern Zhejiang plain have successively undergone the NGC arable land. The engineering measures include the removal of dryland crops, removal of root systems, plough pan remediation, soil fertility remediation, and restoration of rice cultivation, achieving some success. Therefore, project zones undergoing the NGC of arable land in Jiaxing City and Huzhou City, Zhejiang Province were selected as the study area.

Soil sample collection and sequencing

Soil samples were collected before (August 2019) and after (August 2020) the NGC of arable land was implemented (Figure 1). On the basis of the land-use survey data of the project zones, the crop cultivation status of the sampled plots is shown in Table 1. All samples were collected at a temperature of 27–30°C in the absence of rainfall. The S-shape multi-point sampling method was employed to collect 0–10 cm of the topsoil, which was evenly mixed to form a single soil sample weighing 500 g each. The nine project zones were numbered 01 to 09, while samples collected before NGC implementation were labelled A; those collected after NGC implementation were labelled B, yielding a total of 18 samples. A total of 20 g was weighed out from each sample and stored in a −80°C refrigerator. The samples were later sent to Shanghai Genesky Biotech Co., Ltd. for soil bacterial DNA extraction and 16S rDNA amplicon sequencing (Beckers et al., 2016; Wan et al., 2021). DNA extraction was performed in triplicate for each sample (Dimitrov et al., 2017; Wan et al., 2021). The remaining 480 g of the sample was used for soil physicochemical testing.

TABLE 2 Changes in soil environmental factors before (group A) and after (group B) paddy field non-grainization consolidation.

Group	Project zone no.	FIQ	SMI (%)	pH	SOM (g/kg)	AP (mg/kg)	AK (mg/kg)	TN (g/kg)
A	A01	0.7647	38.45	5.42	10.6	34.33	14.78	1.46
	A02	0.6544	47.09	6.32	30.54	74.72	28.93	1.95
	A03	0.7089	43.16	6.28	24.6	56.14	24.98	1.71
	A04	0.6622	46.60	6.42	28.8	70.69	30.21	2.01
	A05	0.6796	44.84	6.11	24.93	56.41	27.07	1.8
	A06	0.6803	41.31	6.16	25.77	61.53	28.31	2.06
	A07	0.7024	45.07	5.92	20.8	59.18	28.43	1.74
	A08	0.7207	40.86	5.73	18.09	40.2	19.2	1.57
	A09	0.771	34.91	5.39	9.2	30.21	14.97	1.44
B	B01	0.7061	34.26	5.61	14.32	35.99	16.9	1.71
	B02	0.6233	44.66	6.51	35.1	76.47	32.1	2.07
	B03	0.6604	37.68	6.42	28.6	67.09	26.85	1.9
	B04	0.6516	44.79	6.51	34.11	80.67	31.08	2.09
	B05	0.6701	43.44	6.24	27.4	74.18	28.36	2.1
	B06	0.6437	39.17	6.26	26.97	64.57	26.64	1.91
	B07	0.684	44.27	5.98	23.7	62.27	28.09	1.89
	B08	0.711	30.77	5.88	18.62	42.09	20.22	1.61
	B09	0.7691	25.14	5.41	10.9	34.44	15.47	1.48

Note: FIQ, Parcel fragmentation; SMI, Soil moisture index; SOM, Soil organic matter; AP, Available phosphorous; AK, Available potassium; TN, Total nitrogen.

TABLE 3 Basic physical and chemical properties of soil samples (Means ± SD).

Group	FIQ	SMI (%)	pH	SOM (g/kg)	AP (mg/kg)	AK (mg/kg)	TN (g/kg)
A	0.70 ± 0.04a	38.24 ± 7.00a	5.97 ± 0.38a	21.48 ± 7.56a	53.71 ± 15.59a	24.10 ± 6.13a	1.75 ± 0.23a
B	0.68 ± 0.04a	42.48 ± 4.01b	6.09 ± 0.40a	24.41 ± 8.36b	59.75 ± 17.77b	25.08 ± 6.06a	1.86 ± 0.22a

Note: Data are means ± standard deviations. Different lowercase letters in the same column of each treatment are significantly different at the 0.05 probability level. FIQ, Parcel fragmentation; SMI, Soil moisture index; SOM, Soil organic matter; AP, Available phosphorous; AK, Available potassium; TN, Total nitrogen.

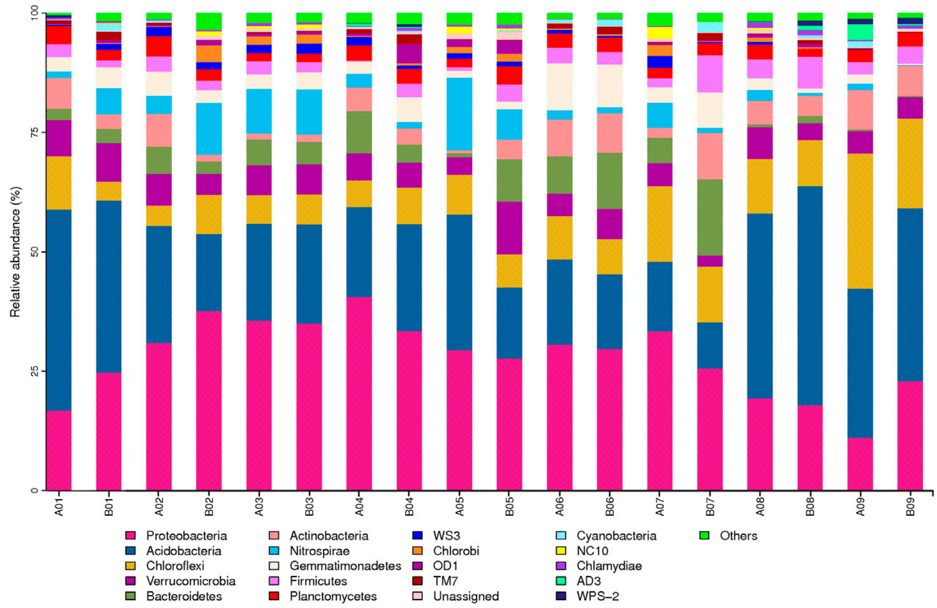

FIGURE 2
Relative abundances of bacteria at the phylum level in soil samples.

Soil sample DNA was extracted using the FastDNA SPIN Kit for Soil. Polymerase chain reaction (PCR) amplification was performed using the ABI GeneAmp® 9,700 thermal cycler and TransStart FastPfu DNA polymerase. PCR amplification products were measured using the QuantiFluor™-ST Fluorometer. The MiSeq library was prepared using the TruSeqTM DNA Sample Prep Kit based on the Illumina HiSeq gene sequencing system. Quality control and filtering were then performed on the sequencing data using the Trimmomatic software, followed by clustering to form operational taxonomic units (OTUs) with 97% identity using the Ribosomal Database Project (RDP) Bayesian classifier on the Usearch platform (version 7.0) and OTU annotation using the Greengenes database (http://greengenes.secondgenome.com).

Measurement of soil environmental factors

Measurements were performed on 7 environmental factors before and after the NGC of arable land in the project zones, which included the soil moisture index (SMI), pH, Soil organic matter content (SOM), available phosphorous (AP), available potassium (AK), total nitrogen (TN), and parcel fragmentation (FIQ). SMI was determined using the oven drying method, in which the samples were dried at 105°C for 6 h in an electric constant-temperature oven. Then, pH was determined using the potentiometric method. SOM was determined using the potassium dichromate volumetric method. AP was measured using an ultraviolet spectrophotometer. AK was measured using a flame photometer (F-100). TN was measured using an automatic Kjeldahl nitrogen analyser (K9860).

FIQ was calculated by the equation

$$FIQ = (N_T - 1)A_{T\,\min}LA_T$$

N_T is the total number of arable patches in the project zone, AT_{min} is the minimum area of a single arable patch in the project zone, and LA_T is the total area of arable patches in the project zone. A smaller FIQ value indicates a larger scale of arable land.

Analysis of soil bacterial communities

Raw DNA sequencing data were processed on the Usearch platform (version 7.0). Then, the RDP classifier module was used

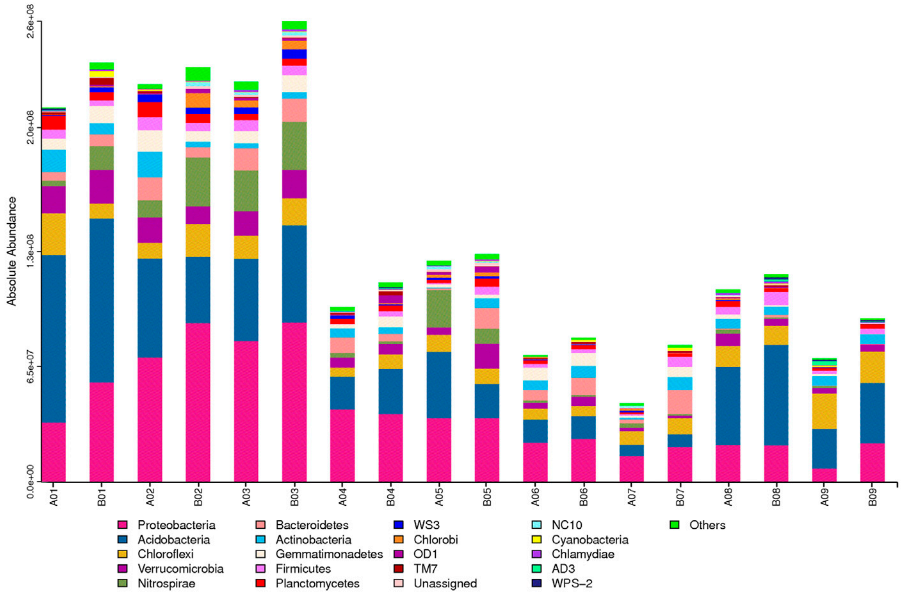

FIGURE 3
Absolute contents of bacteria at the phylum level in soil samples.

TABLE 4 Alpha diversity indices of soil bacteria before (groupA) and after (group B). Paddy fields non-grainization consolidation.

Group	Shannon	Simpson	Chao1	ACE	Coverage
A	0.65 ± 0.024a	0.25 ± 0.029a	0.55 ± 0.028a	0.55 ± 0.028a	0.47 ± 0.027a
B	0.66 ± 0.032a	0.21 ± 0.032a	0.60 ± 0.031a	0.60 ± 0.031a	0.53 ± 0.028b

Note: Data are means ± standard deviations. Different lowercase letters in the same column of each treatment are significantly different at the 0.05 probability level.

to calculate the number of OTUs at a threshold of 97% identity, and the community composition was determined at the phylum level (Tipayno et al., 2018). Based on the results of OTU analysis, the R tool was used to plot and analyse the community composition of soil bacteria. The alpha diversity of the soil bacterial communities was characterized by calculating the Shannon, ACE, Chao1, Coverage and Simpson indices using mothur 1.30.1, which were non-dimensionalised for comparative analysis. Larger Shannon, ACE, Chao1 and Coverage values indicate greater diversity, whereas a higher Simpson value indicates lower diversity (Pitta et al., 2014; Wan et al., 2021). Statistics from Student's test and Wilcoxon rank-sum test were used for the analysis of significant differences indices in diversity between groups. The OTU abundance tables were normalized using the PICRUS software, and the Greengenes OTU IDs were mapped to the COG and KEGG databases to obtain the COG family information and KO information of the corresponding OTUs. Finally, the function abundance profile and the abundances of each functional category were obtained to analyse the changes in soil bacterial function (Langille et al., 2013). The Wilcoxon rank-sum test was performed to test the significance of functional differences in soil bacteria.

Analysis of the effects of environmental factors on soil bacterial diversity and structure

Using the Canoco software, canonical correlation analysis (CCA) was carried out based on the bacterial OTU composition and soil environmental factors to analyse the relationship between soil bacterial community diversity and soil environmental factors before and after the NGC of arable land (Ter Braak, 1986). In addition, to further analyse the correlation between soil bacterial phyla and soil environmental factors, the vegan software package in R was used to perform Spearman's correlation analysis between the two.

Results

Effects of NGC on soil environmental factors

The change characteristics of environmental factor in 18 soil samples showed in Table 2. The comparison of the different items (01–09) in a single group (group A) suggests that there are significant differences in the physicochemical properties of the soil samples at different spatial locations, which indicates the existence of spatial

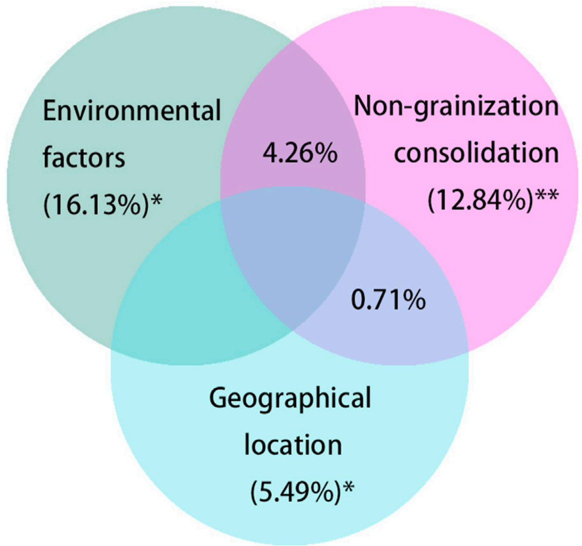

FIGURE 4
VPA Venn diagram of the effects of non-grainization consolidation, environmental factors and geographical location on soil bacteria. Note: Asterisks represent significance level, * and ** corresponding to 0.05 and 0.01 level, respectively. VPA, Variation partitioning analysis.

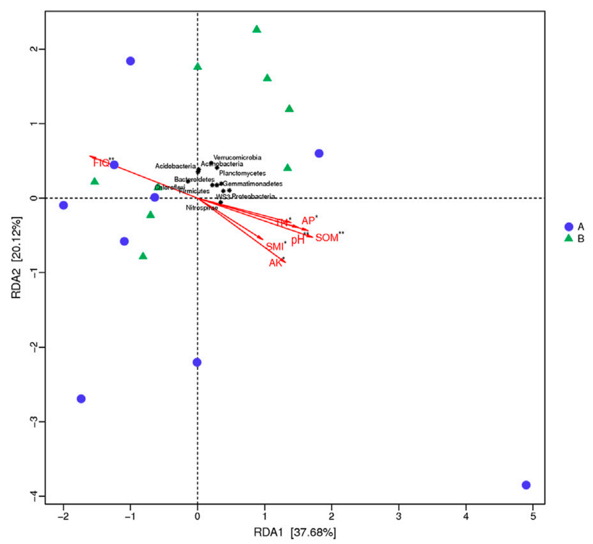

FIGURE 5
RDA ranking of soil bacterial composition and environmental factors. Note: asterisks represent significance level, * indicates 0.01 < $p \leq 0.05$, ** indicates 0.001 < $p \leq 0.01$; RDA, Redundancy Analysis.

heterogeneity in the soil with the exclusion of the deviations in the sampling and measurement process. This study focused on the changes of soil and its microorganisms before and after the implementation of paddy field NGC, thus the subsequent analysis mainly narrowed to analyze the effects of paddy field NGC on soil and its microorganisms by comparing the data of group A and group B.

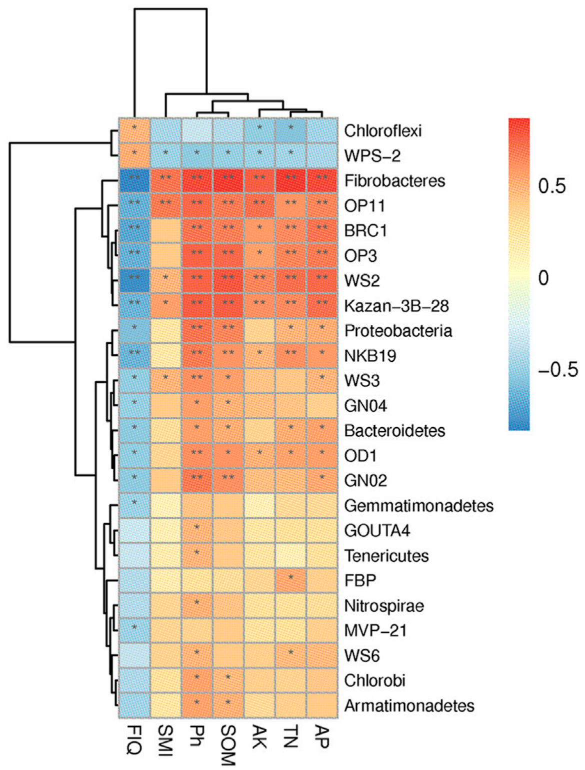

FIGURE 6
Spearman correlation coefficients of soil bacterial phyla and environmental factors.

Table 3 lists the soil environmental factors changes before (group A) and after (group B) the NGC of paddy fields. The results indicate that paddy field NGC increased SMI and reduced FIQ by consolidating plots and re-cultivation of non-grain-producing parcels ($p < 0.05$). pH, SOM, AP, and AK are also increased ($p < 0.05$) after the paddy field NGC, and the soil physical and chemical properties improved obviously.

Effects of NGC on soil bacterial community structure

According to the results for the relative abundances of soil bacteria at the phylum level (Figure 2), the bacteria found in the 18 soil samples obtained from the 9 project zones before and after the paddy field NGC were mainly from the following 11 phyla: Proteobacteria (27.89%), Actinobacteria (25.25%), Chloroflexi (10.02%), Verrucomicrobia (5.69%), Bacteroidetes (4.99%), Acidobacteria (4.75%), Nitrospirae (4.41%), Gemmatimonadetes (3.76%), Firmicutes (3.00%), and Planctomycetes (2.71%), which accounted for 92.47% of the OTUs. In terms of the changes in bacterial relative abundances before and after implementation, Proteobacteria (which has the greatest abundance) increased significantly after implementation in project zones 01, 02, and 09 but decreased in the other project zones. Actinobacteria increased markedly in project zones 03, 04, 08, and 09 but decreased in the other project zones.

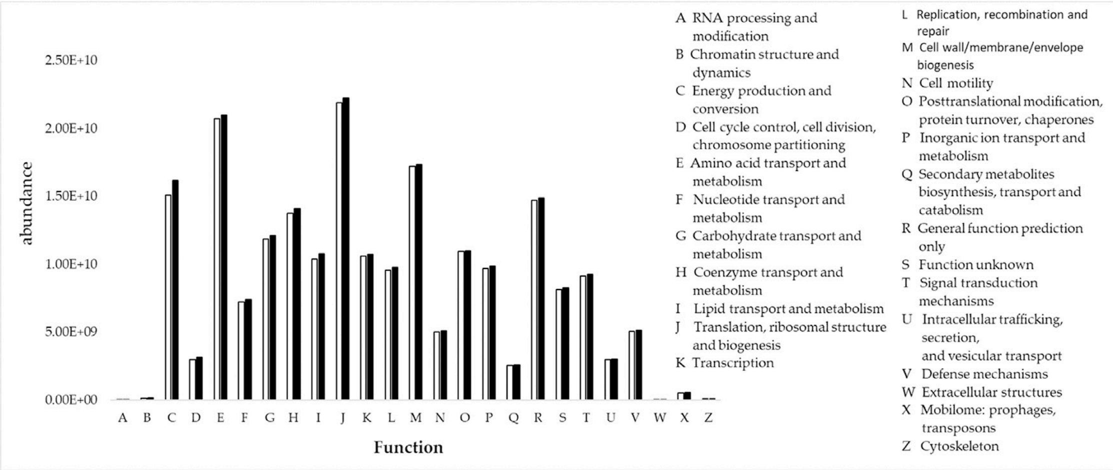

FIGURE 7
PICRUSt inferred functional abundance of soil samples before (white) and after (black) the non-grainization consolidation of paddy fields.

The absolute contents of soil bacteria at the phylum level were calculated (Figure 3), and marked differences were observed in the total amounts of soil bacteria across the different samples, ranging from a minimum of 4.42×10^7 copies/g (A07) to a maximum of 2.61×10^8 copies/g (B03). By comparing the absolute amounts of soil bacteria in soil samples A01 to A09 before the NGC project, it can be seen that the higher absolute amounts of soil bacteria in A01 (planted watermelons), A02 (planted vegetables), and A03 (planted grapes), which were all above 2.11 × 108 copies/g, and the lower will be the absolute amounts of soil bacteria in A05 (planted strawberries), A08 (planted mulberries), A4 (planted blueberries), A06 (planted pear trees), A09 (planted shrubs), and A07 (planted tea) which were all below 1.25 × 108 copies/g, and declined sequentially in absolute soil bacterial amount. This indicates that the planting of different crops on the paddy fields had an impact on the soil bacterial community before the implementation of NGC.

On the other hand, there were marked differences in the trends of change between the absolute content and relative abundance of soil bacteria before and after the NGC of paddy fields. The total amount of soil bacteria was higher after implementation (group B) than that before implementation (group A), with project zone 05 showing the smallest increase (3.05%) and project zone 07 showing the largest increase (74.18%). The absolute content of the dominant phylum, Proteobacteria, increased markedly after implementation in project zones 01, 02, 03, 05, 06, 07, and 09, and decreased slightly in project zones 08 and 04. The relative abundance of soil bacteria is used to indicate the changes in the proportions of the different bacteria within the community, whereas the absolute content is used to indicate the changes in the quantities of the different bacteria. Thus, by integrating these two indicators, we can obtain a more comprehensive and accurate understanding of the effects of arable land NGC on soil bacterial communities (DeAngelis et al., 2015).

Effects of NGC on soil bacterial alpha diversity

The alpha diversity indices of soil bacteria was calculated based on absolute content. Analysis of variance was analyzed using SPSS (version 20) software, Levene's test for chi-squaredness was used, and Tukey's test for significance if the variance was chi-squared, Tamhane T2 test for significance if the variance was not chi-squared.

The results show that NGC is the factor that significantly affects the diversity of bacterial communities ($p < 0.01$) (Table 4). The alpha diversity indices (ACE, Chao1, Coverage, Shannon) of soil bacteria in group B (after NGC implementation) were clearly superior to those in group A (before NGC implementation), implying that engineering measures for paddy field NGC (e.g., re-cultivation of non-grain land, parcel merging, land levelling, ditch construction, and application of organic fertilisers) contributed to improving the alpha diversity of soil bacteria.

The effects of NGC, environmental factors, and geographical location on soil bacterial

Geographical location and environmental factors may play key roles in the mechanism of NGC effects on soil bacterial changes in arable land. Therefore, VPA was employed to determine the effects of NGC, Environmental factors Geographical location (PCNM matrix). The results showed that NGC, Environmental factors and geographical location separately had significant effects on the bacterial (NGC, F = 2.6248, $p < 0.01$; Environmental factors, F = 3.1907, $p < 0.05$; Geographical location, F = 1.0337, $p < 0.05$) (Figure 4). As a result, NGC, Environmental factors and Geographical location interacted and systematically influenced the process of soil bacterial community construction.

Effects of environmental factors on soil bacterial diversity and structure

Redundancy Analysis (RDA) refers to an expanded method of multi-response regression analysis and testing is often used in microbial community analysis to decompose changes in species abundance into variance associated with environmental variables and to explore the significance of community species composition constrained by environmental variables through data testing. The data analysis of RDA and the significance test showed that the environmental factors which were close-knitted with the soil bacterial community structure of the sample sites were TN (r^2 = 0.99797, p = 0.037), AP (r^2 = 0.99560, p = 0.017), pH (r^2 = 0.99536, p = 0.006), SOM (r^2 = 0.98950, p = 0.004), FIQ (r^2 = −0.98068, p = 0.007), SMI (r^2 = 0.90261, p = 0.018), and AK (r^2 = 0.85988, p = 0.024) (Figure 5) were highly correlated with RDA axis 1.

Spearman correlation analysis and test showed that Fibrobacteres, OP11, GN02, WS2, and Kazan-3b-28 etc. in soil samples were significantly correlated with TN, AP, pH, SOM, FIQ, SMI, and AK (p < 0.01) (Figure 6). These findings suggest that paddy field NGC altered the TN, AP, pH, SOM, FIQ, SMI, and AK, which in turn affected the diversity and structure of the soil bacterial communities.

(The figure shows the correlation between environmental factors and soil fungi, with warm tones indicating positive correlation and cool tones indicating negative correlation. * indicates $0.01 < p \leq 0.05$, ** indicates $0.001 < p \leq 0.01$).

Effects of NGC on soil bacterial functions

The 16s rRNA gene is a key tool to researching the function of biological communities. Using PICRUSt software to calculate the corresponding functional abundance of bacterial communities. Wilcoxon rank sum test results showed that soil bacterial functions improved significantly (p < 0.01) after the implementation of paddy field NGC (group B) compared to before the implementation (group A), and there were differences in the magnitude of improvement of each bacterial community function, E amino acid transport and metabolism, C energy production and conversion, T signal transduction mechanism and M Cell membrane biogenesis were the soil bacterial functions that changed significantly before and after project implementation, which was mainly the result of the combined effect of the change in bacterial species dominance and change in quantity (Figure 7).

Discussion

Uncovering the patterns of change in the bacterial communities of arable land is a key topic in the field of sustainable eco-functions protection that has been extensively explored in microbial ecology (Tecon and Or, 2017). However, very few studies have comprehensively examined the patterns of change in the bacterial communities and ecological functions of arable land by combining the three dimensions of species diversity, relative abundance, and absolute abundance. In view of the above, we employed 16S amplicon sequencing to explore the effects of paddy field NGC on soil bacterial communities and ecological functions which through combining the relative abundance and total bacterial quantities. By performing experiments at the parcel scale, we have found powerful evidence supporting the crucial role of NGC engineering in improving the soil bacterial communities and ecological functions of arable land.

The need for economic benefits has driven a gradual increase in the non-grainization of paddy fields in China, which has led to a significant impact on the sustainable ecosystem structure and function of arable land (Su et al., 2020; Li et al., 2022). Changes in land use types and land remediation can significantly affect soil properties and microbial community composition in many areas. Studies, with high-throughput sequencing analyzing the relative abundance of soil bacteria at disposal, reveal the changes in soil bacterial communities (Bai et al., 2022; Li et al., 2016). In this study, we observed that implementing the NGC of paddy fields led to a decrease in the relative abundances of Proteobacteria and Actinobacteria in project zones 05, 06, and 07. Based solely on the decreases found in these two phyla, we can only conclude that the NGC of paddy fields was unfavourable for their growth. However, by calculating the absolute content, we found that the quantities of the two bacterial phyla had increased to some extent after the NGC of paddy fields, with project zone 07 showing increases of up to 33.78% and 17.55% in the absolute contents of Proteobacteria and Actinobacteria, respectively. Previous studies have demonstrated that combined evaluation with relative abundance and absolute content was more suitable for describing the changes in soil bacterial communities (Aitchison, 1982; Ter Braak, 1986; Gloor et al., 2017; Knight et al., 2018; Morton et al., 2019). In ecology, relative abundance is mainly used to describe whether a given species is more or less abundant relative to the rest of the community, whereas absolute content is an indicator that truly describes the actual quantity of a given species (Hubbell and Luis, 2004). Existing studies have reported similar trends involving the improvement of soil bacterial communities by rational land cnsolidation engineering (Lin et al., 2019; Li et al., 2021a). Soil bacteria in paddy fields are significantly affected by the non-grain dryland farming, implying that the non-grainization of paddy fields in the economically developed areas of southern China has exacerbated the loss of soil microbial diversity (Qi et al., 2022). Thus, engineering measures for land consolidation, such as the re-cultivation of rice in non-grain parcels, and the application of organic fertilisers, can effectively prevent the degradation of arable land, the loss of biodiversity, and the decline of paddy field ecosystem functions. Our study also revealed that when evaluating the bacterial community of a single sample, the NGC of paddy fields, the increase in the absolute contents of bacteria at the phylum level was not significant in project zone 02 at 4.27%. Absolute content is better suited to describe and evaluate the actual quantitative changes in soil microbial community structure and the relationships between microorganisms across multiple samples (Lou et al., 2018). Relative abundance is more suitable for describing and evaluating the relationship between microorganisms within a single soil sample (Yang et al., 2018).

The relative abundances indicate that the proportions of Nitrospirae, Chloroflexi, and Chlorobi increased by an order of magnitude. Thus, although paddy field NGC did not significantly increase the quantity of bacteria, it led to increases in Nitrospirae, Chloroflexi, and Chlorobi relative to other bacterial phyla, which were able to improve the capacity for ammonia-nitrite-nitrate conversion and energy production and conversion to a greater extent. According to previous studies, the long-term dryland farming of paddy fields can lead to systematic and abrupt changes in multiple ecosystem attributes (Breidenbach et al., 2017). In particular, our findings suggest that to reduce the negative effects caused by the non-grainization of arable land on the diversity and ecological functions of soil bacterial communities, the changes in soil bacterial diversity and ecological functions should not be overlooked during the formulation of arable land NGC and policies for the management of agricultural production. In short, the two indicators of bacterial community structure (i.e., relative abundance and absolute content) each have their own advantages and disadvantages when used to perform evaluations. Relative abundance is more suitable for describing and evaluating the relationships among different bacteria within a single sample with respect to bacterial community structure. In contrast, absolute content is more suitable for describing and evaluating the actual quantitative variations in bacteria and their community structure, as well as the relationship between bacteria across different samples (Yang et al., 2018; Chen et al., 2020).

Elucidating the mechanisms underlying the effects of paddy field NGC on soil bacterial community and ecological functions has significant implications for better understanding the remediation and maintenance of bacterial diversity and sustainable eco-functions protection in paddy fields. In this study, the comparison of bacterial community structure, relative abundance, and absolute abundance before and after the NGC of paddy fields showed that engineering measures involving the restoration of rice cultivation in non-grain dryland farming were closely associated with the remediation and balance of soil bacterial communities. The parcel-scale experiments conducted in this study further confirmed the association between land consolidation engineering and soil bacterial communities. In particular, the implementation of various engineering measures, such as the removal of dryland crops, removal of root systems, plough pan remediation, remediation of soil fertility, and restoration of rice cultivation, led to the optimisation and improvement of soil bacterial eco-functions. This may be due to the complex interactions between soil bacteria and soil physicochemical properties (Hermans et al., 2020). For example, certain soil bacteria can regulate amino acid transport and metabolic functions, which can provide substrates for crop growth (Wang et al., 2019). The implementation of NGC engineering altered the soil physicochemical properties, optimised the relative abundance and absolute content of soil bacteria, as well as strengthened the amino acid transport and metabolic functions of soil bacteria. In this study, we first established the mechanisms underlying the effects of paddy field NGC on soil bacterial communities and then emphasised the potential role of changes in soil bacterial community structure, relative abundance, and absolute content in achieving the sustainable eco-functions protection of paddy field.

There are certain potential limitations that should be considered within the scope of this study. First, many sequences were obtained from the 16S rDNA high-throughput sequencing of the 18 soil samples, which can provide theoretical support for future studies to some extent. However, since NGC engineering may exert continuous effects on soil microbes, meanwhile, differences in geographic location may also lead to different effects of NGC on soil microbes. Samples from different years and representative areas should be added in future studies to comprehensively reflect the dynamic effects of the different stages and spaces of NGC engineering on soil microbes. In addition, the effects of NGC engineering on soil microbes should be evaluated using a multi-disciplinary approach involving multiple methods to obtain more effective and holistic research conclusions.

Conclusion

In summary, the application of 16S rDNA sequencing technology, together with testification from the two aspects of relative abundance and absolute content, verifies that the non-grain paddy field rearrangement has changed the soil bacterial community structure and improved the soil bacterial diversity, which will profoundly affect the sustainability of paddy field ecological function. Therefore, it is urgent to incorporate the diversity of soil bacterial diversity and its ecological significance of non-grain paddy field rearrangement into the research framework and theoretical system of ecological protection of cultivated land. Meanwhile, it should be noted that since this observative study only focuses on the changes before and after the implementation of non-grain paddy field rearrangement within one year span, it is still uncertain for the author to reach qualitative outcomes, that is, whether the results of this study are the temporary response or long-term impact on soil bacterial diversity to non-grain remediation in paddy fields. In addition, the results also justify the positive response between soil environmental factors and soil bacterial function and non-grain paddy field remediation. Therefore, it needs further effort to ponder over the coupling research between soil bacteria and environmental factors and the evolution process of various ecological functions in cultivated land to further reveal the nutrient differences of paddy ecosystem caused by the change of soil bacterial community under non-grain paddy field rearrangement and its feedback effect on the sustainability of ecological functions, and most importantly to provide a scientific basis for optimizing the diversity of soil bacterial communities and the sustainable protection of paddy ecological functions under non-grain remediation.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://www.ncbi.nlm.nih.gov/, PRJNA839191.

Author contributions

BG: Conceptualization, methodology, data curation, validation, and supervision. YL: Investigation, software, writing- original draft preparation, writing- reviewing, and editing.

Funding

This study was supported by the National Natural Science Foundation of China (NO. 42201288).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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TYPE Original Research
PUBLISHED 29 March 2023
DOI 10.3389/fenvs.2023.1134271

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SPECIALTY SECTION
This article was submitted to Land Use Dynamics,
a section of the journal
Frontiers in Environmental Science

RECEIVED 30 December 2022
ACCEPTED 20 March 2023
PUBLISHED 29 March 2023

CITATION
Du G, Xie J, Hou D and Yu F (2023), Regional differences in the green use level of cultivated land in the Heilongjiang reclamation area.
Front. Environ. Sci. 11:1134271.
doi: 10.3389/fenvs.2023.1134271

Regional differences in the green use level of cultivated land in the Heilongjiang reclamation area

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Scientific understanding of the connotation of Green Use of Cultivated Land (GU-CL) is important to promote sustainable use of cultivated land. This study aims to analyze the regional heterogeneity of the Green Use Level of Cultivated Land (GUL-CL) in Heilongjiang Reclamation Area (HRA). Using entropy power method and coupled coordination degree model, statistical analysis was carried out based on the data of the HRA in 2020. The results show that the degree of GUL-CL in the study area is generally well-developed, but internal differences exist. Specifically, the GUL-CL ranges from 0.590 to 38.179, with a mean value of 8.818. Additionally, 29.204% of the total farms are above the higher level, mainly in Jiansanjiang and Baoquanling. In environmental friendliness practices, the high-level areas are concentrated primarily on the Songnen Plain Reclamation Area. Or, the Sanjiang Plain Reclamation Area positively presents significant effects on resource conservation. In the study area, spatial intensification and output efficiency are relatively balanced. The coupling coordination degree of green use of cultivated land (GU-CL) (0.20–0.50) is at a low coupling coordination stage. Consequently, this study can provide practical knowledge for the GU-CL in the black soil region of Northeast China.

KEYWORDS

cultivated land use, the green use level of cultivated land, regional differences, black-soil areas, heilongjiang reclamation area

1 Introduction

China has achieved food security by investing large investments in labor and technology for cultivated land use over the past three decades (Chai et al., 2023). However, the large amount of elemental input has caused increasingly serious negative environmental impacts on cultivated land (Zambon et al., 2017; Zhou et al., 2021). For example, continuous fertilizer and pesticide use have caused soil acidification, erosion, water pollution, and other negative environmental impacts (German et al., 2017; Yu et al., 2019; Ye et al., 2022). With the introduction of the UN Sustainable Development Goals (SDGs) (especially Goals 12 and 13) and the "green" transformation of the food system (Yue et al., 2022), there is an urgent need to comprehensively assess and upgrade the green development of China's cultivated land (Bryan et al., 2018).

The report of the 19th National Congress of the Communist Party of China points out that "we will unswervingly implement the new development concept and form a green way of development and lifestyle." In the same perspective, "The 14th Five-Year Plan again emphasizes the promotion of green development, the comprehensive green transformation of economic and social development, and the construction of a modernization in which people and nature live harmoniously. Green use of cultivated land is the focus of green development. It is a fundamental principle that must be adhered to and implemented in current land use and management, affecting global environmental change and sustainable development of regional society and economy (Lai et al., 2020; Ma et al., 2020).

Green use of cultivated land is based on the natural properties of land, but its essence is the social phenomenon of using land (Wei et al., 2021). Green utilization requires not only the support of natural science but also the change of concept and the adjustment of social relations.

Currently, many scientific studies on GU-CL framework construction focus on the factors such as the triple types population-economic-social-environment (ke et al., 2021) and environment-resource-ecology-quality (Yu et al., 2022; Chai et al., 2023). (Note: In this paper, we use GU-CL to refer to the green use of cultivated land, and in quantifying the change in GU-CL, we use GUL-CL to refer to the level of green use of cultivated land). Meanwhile, many studies related to the GU-CL concept have evaluated and investigated the quality of cultivated land, sustainable use of cultivated land (Peltonen-Sainio et al., 2019; Li et al., 2023), and ecological security of cultivated land (Chen et al., 2021). The focus is on selecting relevant indicators by measuring the conceptual relationships between environmental risks, functions, or ecosystem services of cultivated land (Rinot et al., 2019; Ye et al., 2022). In general, there are three main indicators: (1) The degree of land use sustainability or efficiency by screening the mobile elements (labor, technology, capital, *etc.*) in the cultivated land system using the cultivated land input-output relationship. This situation mainly includes the intensity of fertilizer or pesticide use, effective irrigated area, multi-crop index, food production, agricultural yield, and carbon emissions (Kuang et al., 2020; Lu et al., 2020). (2) The health of the cultivated land system is determined by selecting the level of socio-environmental governance and technological control attached to the cultivated land system. This context mainly includes irrigation and drainage conditions, accessibility of field roads, level of disaster prevention and control, and level of agricultural mechanization (Ye et al., 2022; Zhang et al., 2022). (3) Reflecting the government's support and intensification of cultivated land through national policies and implementation of land improvement (Ke et al., 2021). This category includes energy conservation and environmental protection expenditure, investment in fixed assets, agricultural land for facilities, and cultivated land replanting index.

The above focuses on the green dynamics of cultivated land use, which provides an important reference for accurately grasping the connotation and essentials of GU-CL, evaluation methods, and path selection. However, the fragmented explanatory mechanism of the existing literature fails to reveal the core meaning of GU-CL. Cultivated land is an artificial utilization system with multiple attributes, such as natural, social, and economic environments (Li and Liu, 2021). Existing evaluations have paid more attention to people's material demand for cultivated land utilization and the core productive function of cultivated land (Song et al., 2022). To a large extent, the environmental impact of cultivated land and the spatial intensification of cultivated land should also be considered in the index system, such as organic fertilizers, green pesticides, and high-standard farmland, to form a more scientific evaluation index.

As one of the four predominantly black soil areas worldwide, the Northeast Black Soil Region is an important commercial grain production base in China. Due to long-term high-intensity and unreasonable utilization and excessive input of agricultural production chemicals, the natural fertility of black land has been decreasing year by year (Liu et al., 2010; Xu, 2019). The black soil area in northeast China has been gradually transformed from an "ecological functional area" to an "ecological fragile area." Heilongjiang Reclamation Area is located in the Northeast Black Soil's core and has modernized agriculture (Note: this article use HRA to refer to the Heilongjiang Reclamation Area). When General Secretary Xi Jinping visited the HRA in September 2018, he clearly pointed out the need to accelerate the development of green agriculture, adhere to the combination of use and nourishment, and take adequate measures to protect the black land. At the beginning of the 21st century, HRA started to build a national ecological demonstration area, insisting on a "high quality, green and safe" orientation and taking green actions such as "weight loss, drug, and herbicide reduction," rapidly improving the ecological safety of cultivated land. In 2010, HRA was named as "National Modernized Large Agricultural Demonstration Area." Therefore, the region could serve as a 'natural experiment' to understand the level of green use of modern agricultural land, which has specific significance for black soil conservation and provides an excellent example of the sustainable development goals of the Northeast Black Soil Region.

Because it provides a practical basis for carrying out GU-CL in the black soil area of northeast China, this research chose HRA as a case study. The main objective of this study was to clarify the concept and connotation of GU-CL and to explore GUL-CL characteristics and regional differences. The data used in this study were collected from the HRA database in 2021. Based on research data, we used the entropy weight method and coupled coordination model to analyze the regional characteristics and degree of coordination of GUL-CL. Our specific research objectives were to (1) establish the assessment system of GU-CL following defining the concept, (2) comprehensively explore the characteristics and regional differences of GUL-CL in HRA, and (3) analyze the characteristics of coupled coordination degree of GU-CL.

2 Study area

Heilongjiang Reclamation Area (HRA) is located in the four major black soil belts in the world, between 123°40′–134°40′E and 40°10′–50°20′N, mainly in the Songnen Plain and the Sanjiang Plain. It has nine branches and 113 farms, involving 74 counties in 12 cities in Heilongjiang Province (Figure 1). The Sanjiang Plain Reclamation Area is located in the humid and semi-humid low plains, with four branches in Baoquanling, Hongxinglong, Jiansanjiang, and Mudanjiang. The Songnen Plain Reclamation Area is located in a black soil area of China with a diffuse river and mango landscape, with five branches in Beian, Jiusan, Qiqihar, Suihua, and Harbin (Du et al., 2021). In 2020, the cultivated land area was 2.972 million hm^2, of which 2.893 million hm^2 will be sown with grain crops, and the total grain output will reach 21.340 million tons. The agricultural machinery rate was 99.70% in 2020 (accessed on 15 October 2022, at

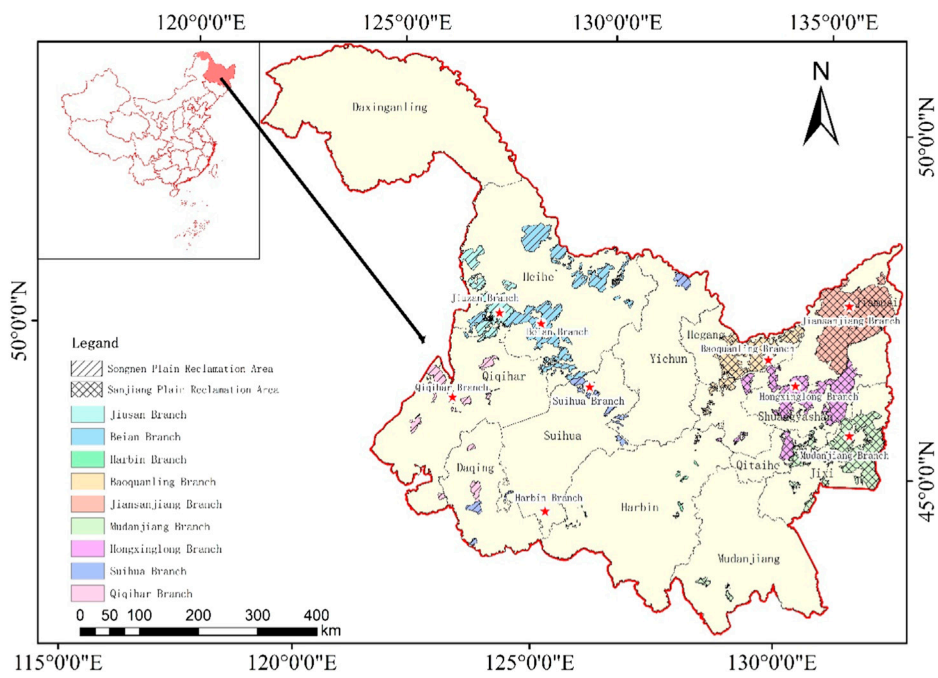

FIGURE 1
Heilongjiang Reclamation Area spatial distribution map.

https://data.cnki.net). Since the beginning of the twenty-first century, HRA has taken several measures to carry out ecological agriculture. For instance, the most important actions were the development of low-carbon agriculture, the promotion of no-till technology, and the return of straw to the field. In addition, previous studies highlighted the launch of the "three reductions" work and the appropriate use of resources and other measures. The main goal is to improve the quality of agricultural products and ensure national food security.

3 Materials and methods

3.1 Source of data

This study was based on 2000–2020 land use data derived from the 1:100,000 national land use database of the Chinese Academy of Sciences (accessed on 26 January 2022, at https://www.resdc.cn). This land use database is combined with multivariate remote sensing image data for human-computer interactive interpretation and then verified by field survey and sampling, with an accuracy of more than 95% (Ning et al., 2018).

The data involved in this paper are organic fertilizer application intensity, green pesticide application intensity, straw return area ratio, conservation tillage area ratio, water-saving irrigation area ratio, surface water substitution for groundwater, agricultural electricity intensity, the total power of agricultural machinery per land unit, unmanned farming area, high-standard cultivated land coverage, multiple cropping index, total agricultural output value, total plantation output value, and plantation population. These data came from the Heilongjiang Reclamation Area Statistical Yearbook (2021) (accessed on 15 June 2022, at https://data.cnki.net) and the economic and social statistical synopsis of Beidahuang Group in 2020.

3.2 Definition and framework

Cultivated land is an important natural resource, and its exploitation is an agricultural production activity in which people use inputs for a specific purpose. At the same time, "green" is a dynamic orientation to change to a green development mode, which is a "green" transformation of the original behavior pattern (Zou, 2019). With the development of the social economy, food safety, environmental health, and landscape recreation have become the focus of urban and rural residents' needs. The ecological value of cultivated land has become prominent (Ke et al., 2021), and agricultural production needs to change from a high-input, high-output model to a sustainable and intensive one (Ye et al., 2020).

GU-CL is an inevitable requirement for green agricultural development and an essential means of ecological civilization construction. Scientific evaluation is based on a clear understanding of the idea of GU-CL, which is also the key to making sustainable use of cultivated land resources. Based on the above knowledge, the green development concept of harmonious coexistence between humans and nature and sustainable development is introduced into the process of cultivated land use, and a preliminary understanding of the GU-CL is formed.

Based on this context, the GU-CL is intended to change the traditional way of using cultivated land. Which is "high input, high consumption, and high pollution," and to use modern advanced agricultural technology to promote safe, high-quality, and efficient

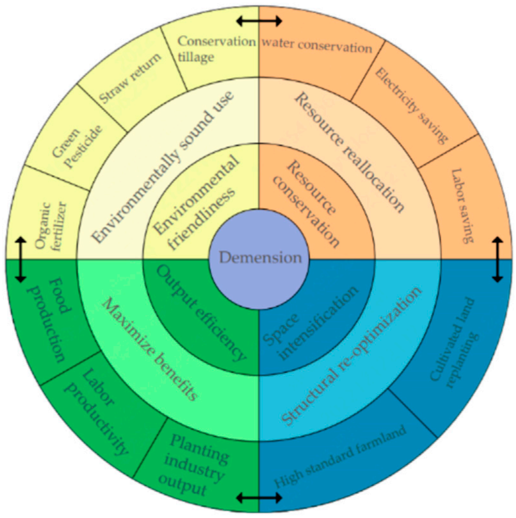

FIGURE 2
Green use of cultivated land concept diagram.

output from cultivated land. It will reduce the environmental pollution caused by using cultivated land, eliminating the excessive use of natural resources. Simultaneously, it may transform the agricultural development mode, optimize the use of spatial structure, and promote the formation of a new pattern of high-quality farm development with a suitable ecological environment, resource conservation, intensive spatial management, and high-quality product supply. Figure 2.

Environmental friendliness and resource conservation are the basic features of GU-CL, space intensification is the means of GU-CL, and output efficiency is the goal of GU-CL. Environmental friendliness and resource conservation are related to green utilization and low-carbon development. Resource conservation and space intensification are in the relationship of scale operation and resource conservation. The relationship between spatial intensification and output efficiency is related to enhanced intensive land use, which increases food production. Or the relationship between output efficiency and environmental friendliness presents the relationship between a green environment and high-quality products. The ultimate goal of GU-CL is to achieve high efficiency, green and high output of cultivated land.

The premise of establishing the indicator system must comply with scientific, systematic, understandable, and operable principles. In this study, regarding the existing studies of relevant scholars (Ke et al., 2021; Chai et al., 2023) and according to the actual situation of cultivated land use in the HRA, the focus is on the construction of the indicator system of GU-CL in four aspects: environmental friendliness, resource conservation, spatial intensification, and output efficiency (Table 1).

(1) Environmental friendliness. This study's understanding of environmental friendliness is the homogeneity and unity of agricultural development and resource environmental protection, as well as the harmony and balance of agricultural development's quantitative and qualitative benefits. Through adopting green production techniques such as organic fertilizers, and green pesticides, the nutrient content of the soil is improved, and the negative impact of the agricultural production process on the environment is reduced. The adoption of conservation tillage and straw return tillage is conducive to reducing soil erosion (Harper et al., 2018) and improving the carrying capacity of the regional agricultural environment. Therefore, the intensity of organic

TABLE 1 Construction of the GUL-CL in the Heilongjiang reclamation area (HRA).

First-level	Second-level	Unit	Attribute	Weight
Environmental friendliness	Organic fertilizer application intensity	kg/hm^2	+	0.204
	Green pesticide application intensity	kg/hm^2	+	0.272
	Percentage of straw return area	%	+	0.010
	Percentage of area under conservation tillage	%	+	0.119
Resource conservation	Water-saving irrigation area ratio	%	+	0.034
	surface water replacement for groundwater irrigation	m^3	+	0.189
	Electricity intensity for agriculture	kW.h/million	-	0.002
	Total power of agricultural machinery per land	kW/hm^2	-	0.001
	Percentage of unmanned farming area	%	+	0.091
Space intensification	High standard farmland coverage rate	%	+	0.030
	Multiple cropping index	-	+	0.002
Output efficiency	Average land value of total plantation production	Million Yuan/hm^2	+	0.019
	Average land grain production	t/hm^2	+	0.009
	Labor productivity	Million Yuan/per person	+	0.018

TABLE 2 The classification of coupling degree.

Coupling degree C	[0, 0.3]	(0.3, 0.5]	(0.5, 0.8]	(0.8, 1]
Type	Weak coupling	Moderate coupling	Moderate strong coupling	Strong coupling

fertilizer application, green pesticide application, straw return ratio, and conservation tillage ratio are selected to characterize environmental friendliness.

(2) Resource conservation. Resource conservation is the primary feature of green development in agriculture, which is to obtain the maximum agricultural profit by minimizing resource consumption and improving resource allocation efficiency. The level of agricultural mechanization is an important manifestation of agricultural modernization. Still, the consumption of energy and resources from agricultural machinery is too high, and the use of large farm machinery in HRA has led to the aggravation of soil slabbing. Affected by the persistently high price of coal, many regions take measures to pull the plug and restrict electricity, affecting agricultural production. With increasing rice cultivation in HRA, groundwater resources are continuously stressed. Unmanned farming can realize smart agriculture, improving operational efficiency and saving planting costs (Wang et al., 2021). Therefore, the total power of agricultural machinery per land, agricultural electricity intensity, surface water replacement for groundwater irrigation, the proportion of water-saving irrigation areas, and the proportion of unmanned farming are selected to characterize resource saving.

(3) Space intensification. There are few high-quality cultivated land resources and insufficient cultivated land reserve resources. Hence, to ensure national food security and meet human demand for agricultural products, the only way to achieve the dual purpose of increasing production and saving land is to explore cultivated land. Also, it depends on optimizing the structure of cultivated land use and promoting the optimal allocation of cultivated land resources. High-standard cultivated land is permanent core cultivated land with flat land that is concentrated and continuous, matching cultivated land and fertile soil, which can maximize the use of high-quality cultivated land resources and increase food production. Therefore, the multiple cropping index and the high standard farmland coverage rate are selected to characterize the spatial intensification dimension.

(4) Output efficiency. Output efficiency is the direct goal of the green use of cultivated land. It is an important driver of the green use of cultivated land, emphasizing the balance between quantity and output quality. The total output value of the planting industry and food production reflect a region's cultivated land production capacity and are important ways to reflect the output efficiency of cultivated land. In the context of labor demonetization, the increase in labor productivity can compensate for the impact of the agricultural labor shortage. Therefore, the average land value of gross plantation output, the average land value of grain production, and labor productivity are selected to characterize output efficiency.

3.3 Research methods

3.3.1 Entropy weight method

According to the positive and negative efficacy and importance of the evaluation indexes, the raw data of each index were normalized using the polar difference standardization method, and the values were taken in the range [0, 1].

Step 1: Standardization of indicators:

$$\text{Negative indicators: } I_{ij} = \frac{X_{\max} - X_{j}^{i}}{X_{\max} - X_{\min}} \quad (1)$$

$$\text{Positive indicators: } I_{ij} = \frac{X_{j}^{i} - X_{\min}}{X_{\max} - X_{\min}} \quad (2)$$

Where: I_{ij} is the standardized value of indicator j of the i sample, i = 1, 2, 3, . . ., n (n indicates the sample size); X_{j}^{i} is the original value of indicator j of the i sample; X_{max} is the maximum value of indicator j, and X_{min} is the minimum value of the j indicator.

The indicators were assigned with reference to existing literature, and the entropy weighting method was applied to assign the indicators and determine the indicator weights (Table 1).

3.3.2 Comprehensive evaluation model

The standardized values and index weights were multiplied and summed based on data standardization to measure the environmental friendliness, resource conservation, spatial intensification, output efficiency, and comprehensive level of GU-CL. The specific formulas are as follows.

$$S_{k}^{i} = \sum_{i=1}^{m} \left(I_{ij} \times W_{ij} \right) * 100 \quad (3)$$

Where: S_{k}^{i} is the comprehensive index of the kth dimension of green use of cultivated land in the i sample; k represents environmental friendliness, resource conservation, spatial intensification, and output efficiency; m is the number of indicators under the k dimension; I_{ij} is the standardized value of indicators; W_{ij} is the weight of j indicators under the i dimension.

3.3.3 The coupling coordination degree model

GU-CL is an integrated system consisting of four subsystems: environmental friendliness, resource conservation, spatial intensification, and output efficiency, and the subsystems present a correlation relationship of interaction and mutual constraints with each other.

The coupling degree is a response to the influence relationship between the subsystems with each other, focusing on the strength of the interaction relationship between the subsystems (Zambon et al., 2017; Dong et al., 2021). However, the coupling degree only emphasizes the interaction relationship between subsystems. In contrast, the coupling coordination

TABLE 3 The classification of coupling coordinating degree.

Coupling coordination degree D	[0, 0.2]	(0.2, 0.4]	(0.4, 0.5]	(0.5, 0.7]	(0.7, 0.9]	(0.9, 1]
Type	Severe imbalance	Moderate imbalance	Basic coordination	Moderate coordination	Advanced coordination	Strong coordination

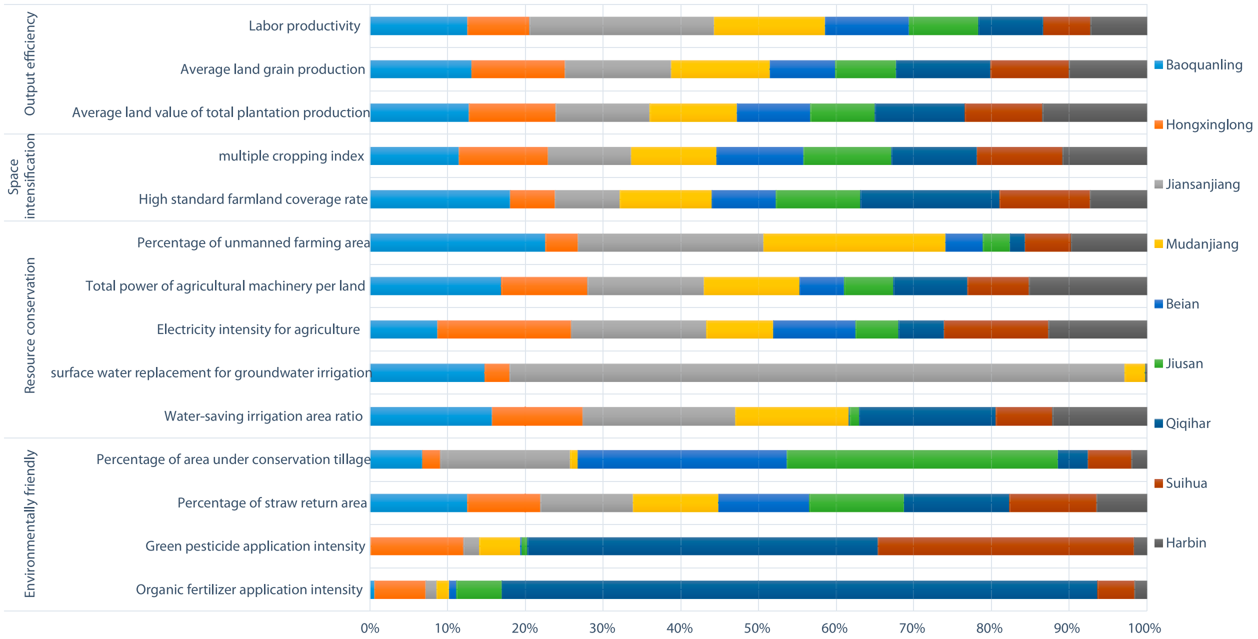

FIGURE 3
The green use factors of cultivated land in HRA (%).

degree can reflect the overall coordinated development of subsystems and reflect the degree of contribution of subsystems to the development of the system (Yang et al., 2020). Therefore, the coupling coordination degree is introduced to reflect the overall coordinated development of GU-CL. The coupled coordination degree model is as follows:

$$C = \left(\frac{U_1 * U_2 * U_3 * U_4}{\left(\frac{U_1 * U_2 * U_3 * U_4}{4} \right)^4} \right)^{\frac{1}{4}} \tag{4}$$

$$T = a*U_1 + b*U_2 + c*U_3 + d*U_4 \tag{5}$$

$$D = (C*T)^{\frac{1}{2}} \tag{6}$$

In this formula, C is the coupling degree. D is the coupling coordination degree. T is the comprehensive reconciliation index of the four subsystems of green use of cultivated land. U_1, U_2, U_3, and U_4 represent the evaluation values of environment-friendly, resource-saving, space-intensive, and output-efficient subsystems; a, b, c, and d are the parameters to be evaluated, and $a + b + c + d = 1$. The paper considers that the four significant systems are equally crucial for the green use of cultivated land, so a, b, c, and d are taken as 0.25. Concerning the relevant research results (Xu et al., 2020) and combined with the actual paper, the coupling degree is divided into four types (Table 2), and the coordination degree is divided into six classes (Table 3).

4 Results

4.1 A single factor for assessing the GUL-CL

According to the results of the single-factor evaluation of GU-CL, there are obvious differences in different GU-CL indicators in the same region (Figure 3). At the level of environmental friendliness, there are obvious differences in organic fertilizer, green pesticide application intensity, and conservation tillage. Qiqihar has outstanding performance in organic fertilizer and green pesticide application intensity, accounting for 76.663% and 45.143% of the total value. Conversely, the lowest is Baoquanling, with 0.641% and 0.089% of organic fertilizer and green pesticide application intensity. The highest percentage of conservation tillage in Jiu San reached 34.909%, and the lowest was Mudanjiang, with 0.979%. Since 2008, China has prioritized the return of straw to the field. Each branch has a high proportion of straw return to the area, with Qiqihar and Baoquanling achieving all straw return to the field and Harbin having a relatively low rate of straw return to the field. At the level of resource conservation, the ratio of water-saving irrigation area varies widely among branches, and the ratio of water-saving irrigation area in Jiansanjiang accounts for 17.634% of the total value. Or the lowest is registered in Beian at 0.454%. All branches except Suihua take surface water to replace groundwater,

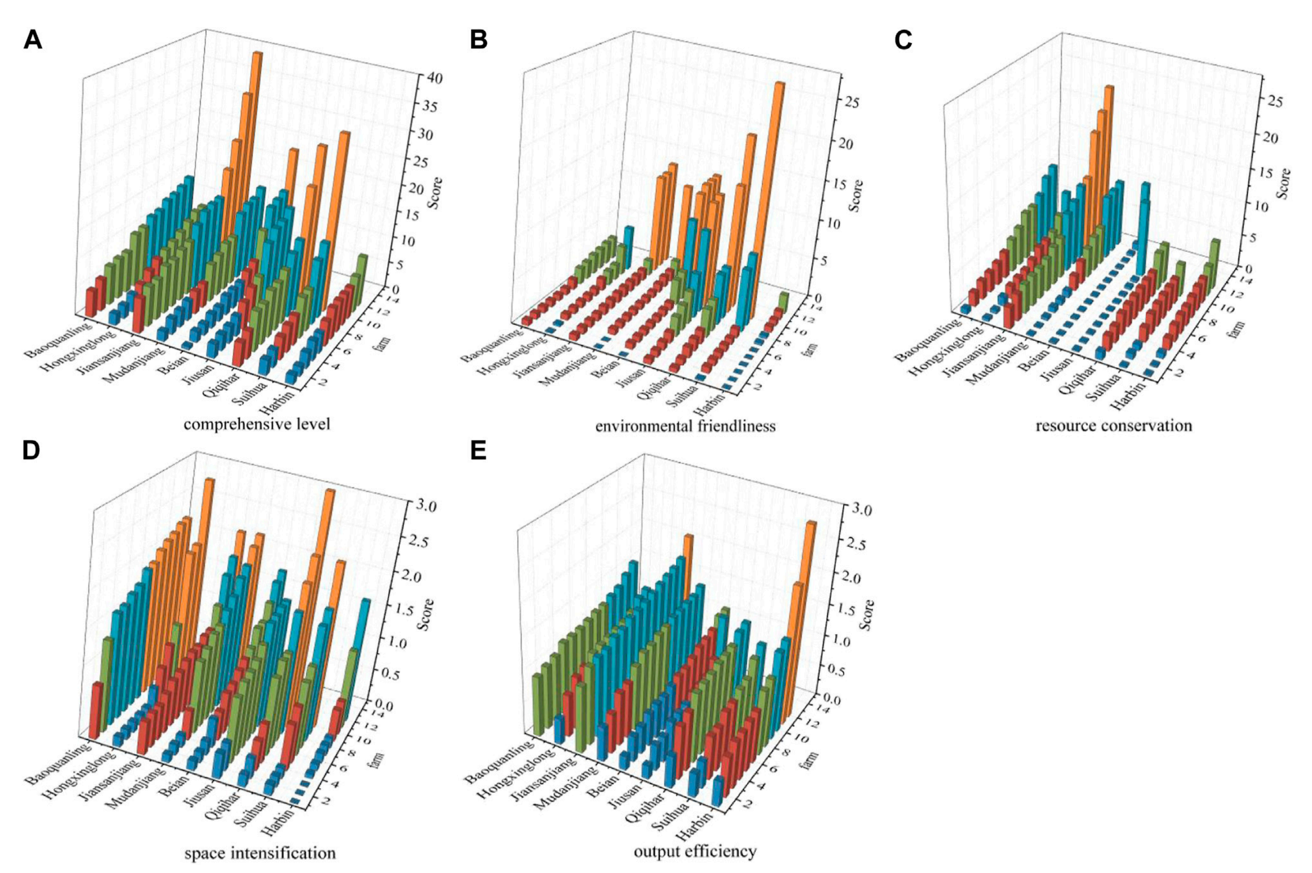

FIGURE 4
GUL-CL in heilongjiang reclamation area.

of which Jiansanjiang is the highest, accounting for 79.220% of the total value. Jiansanjiang (17.379%) and Hongxinglong (17.218%) counties have the highest agricultural electricity intensity per unit area, superior to the average of 11.111%.

In contrast, Jiusan (5.56) and Qiqihaer (5.87) have the lowest, inferior to the average. The total power of agricultural machinery was the highest in Baoquanling, accounting for 16.905% of the total value; conversely, the lowest was in Beian, accounting for 5.767% of the total value. The proportion of unmanned farming varies significantly, with Jiansanjiang and Mudanjiang at more than 23.404% and Qiqihar at the lowest, accounting for only 1.959% of the total value.

At the level of spatial intensification, the coverage rate of high-standard cultivated land varies widely among branches, with Baoquanling and Qiqihar having higher coverage rates of high-standard farmland, accounting for 18.077% and 17.921% of the total value, respectively. Or Hongxinglong has the lowest, accounting for 5.767% of the total value. The land use rate in Northeast China is high but limited by climatic conditions, namely, heat. The multiple cropping index is relatively stable, between 78% and 102% (Xie and Liu, 2015). The average value of the multiple cropping index in HRA was 98.020%, with slight differences among branches.

At the level of output efficiency, the highest average land value of total planting output was 23.61 million yuan/hm^2 in Harbin, accounting for 13.405% of the total value. The lowest value was 14.68 million yuan/hm^2 in Jiusan, accounting for 9.420% of the total value. The highest average land grain production is Jiansanjiang, accounting for 13.697% of the total value, and the lowest is Jiusan, accounting for 7.878% of the total value. The highest labor productivity was in Jiansanjiang (276.5 million yuan/person), accounting for 23.783% of the total value. The lowest was in Suihua (70.54 million yuan/person), accounting for 6.067% of the total value.

4.2 Evaluation results of GUL-CL in HRA

Based on the GUL-CL in 113 farms in the HRA, the natural breakpoint method was used to classify the environmental friendliness, resource conservation, space intensification, output efficiency, and comprehensive levels into five levels: high-level area, higher-level area, medium-level area, lower level area, and low-level area, respectively (Figure 4), and then analyze their regional differences.

The overall development of the GUL-CL in the HRA is appreciable. The study results show that 65 farms with a medium or above-cultivated land green use level accounted for 57.522% of the total evaluation units. Among them, 33 farms record higher status or above, accounting for 29.204% t of the total evaluation units. These counties are mainly distributed along the branches of

Jiansanjiang and Baoquanling in the northern part of the Sanjiang Plain. In these counties, the protection of cultivated land ecology was appreciable. This achievement may be the backbone of the good results they record in the degree of green land use on cultivated land. Lower-level farms are mainly distributed in branches such as Beian and Harbin. However, there are significant differences in the development of each farm. The extensive GUL-CL ranges from 0.590 to 38.179, with a mean value of 8.818. And 54 farms are above the mean value, accounting for 47.788% of the total amount.

At the environmental friendliness level, there are 21 farms in the higher level zone and above, mainly concentrated in the Songnen Plain Reclamation Area, accounting for 76.19% of the total. However, low-level areas are also focused in the Songnen Plain Reclamation Area, mainly in Harbin Branch. There are ten low-level area farms in total, among which eight low-level area farms in Harbin Branch, accounting for 80%. The Sanjiang Plain Reclamation Area is mainly concentrated in medium and lower-level areas. Contrary to environmental friendliness, the Sanjiang Plain Reclamation Area effectively conserves resources. There are 16 farms in the higher level zone and above, with 87.5% in the Sanjiang Plain Reclamation Area, of which Jiansanjiang is particularly outstanding.

In contrast, the Songnen Plain Reclamation Area is mainly concentrated in lower and below-level areas. At the level of spatial intensification and output efficiency, the overall development of HRA is relatively balanced. In recent years, HRA has been improving the basic conditions of agricultural production, carrying out land improvement projects, transforming low and medium-yielding fields, and building high-standard farmland to form a large-scale and diversified landscape pattern.

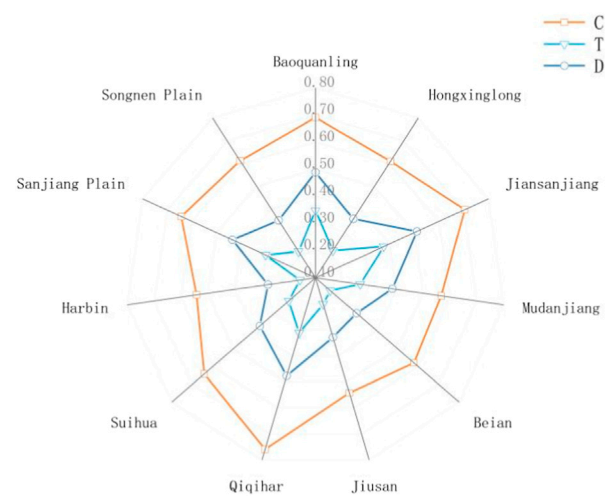

FIGURE 5
Coupling and coordination degree of GU-CL in HRA.

4.3 Analysis of the coupled coordination of GU-CL in HRA

The mean value of the coupling degree of the four major systems of GU-CL in HRA is 0.626. These results ranged between 0.600 and 0.800. The strong coupling state indicates that the four significant subsystems of GU-CL in HRA are relatively close. The subsystems have a benign coupling characteristic, mutual checks and balances, and cooperation. Spatially, the coupling degree of each branch varies significantly. Qiqihar (0.759) and Jiansanjiang (0.704) have a high degree of coupling, and the development of the cultivated land green use subsystem is at the same pace. Mudanjiang, Jiusan, and Harbin have a relatively low degree of coupling, and the development of each subsystem is uneven. The coupling degree of cultivated land resource-environment-space-economy is also above 0.610 for the Sanjiang Plain and the Songnen Plain Reclamation Area in the west, which are in a strong coupling stage. The coupling degree in the Sanjiang Plain Reclamation Area is generally higher than in the Songnen Plain Reclamation Area.

The coupling coordination degrees of the four significant subsystems of GU-CL in HRA are concentrated in the distribution of 0.200–0.500. Consequently, the study results show that there are still many gaps for improvement in high coordination. In the same sense, 23 farms had a coupling degree of moderate coordination or higher, accounting for 20.35% of the farms with high coupling coordination. In contrast, the results highlighted 29 farms with coupling degrees in the stage of essential coordination, accounting for 25.66% of the total, with an average level of coupling coordination. In these areas, 53.98% of the farms have a coupling degree between moderate and severe dissonance. The level of coupling coordination in these areas is weak, and these areas need to focus on strengthening support in the future.

The coordination degree of the cultivated land green use subsystem in the HRA is low, which cannot form a synergy for the high-quality development of cultivated land green use and can hardly play the role of mutual promotion. Spatially, although the level of coordination in the Sanjiang Plain is higher than that in the Songnen Plain, it still needs to be strengthened. As a result, improving the coordination of cultivated land resource-environment-spatial-economy is the way forward in HRA for achieving sustainable cultivated land development and green agricultural development. Figure 5.

5 Discussion

5.1 Evolution of green cultivated land and its influences factors

National policies, economic efficiency, social needs, and scientific and technological progress influence the GUL-CL. Chinese President Xi Jinping attaches great importance to and has repeatedly given important instructions, clearly requiring that strong measures must be taken to protect the black land strategically. Relevant central departments have specifically formulated and implemented policy documents such as "Northeast Blackland Conservation Planning Outline (2017–2030) (Ministry of Agriculture, 2017)" and "Northeast Blackland Conservation Farming Action Plan (2020–2025) (Ministry of Agriculture, 2020)", and local regulations and ordinances have been introduced in Liaoning, Jilin, Heilongjiang and Inner Mongolia. Thus, the study result shows a strong relationship between the GU-

CL and policy. HRA focuses on black soil conservation, soil nutrient balance, water-saving irrigation, conservation tillage, soil erosion control, and other measures. GU-CL has entered a new track of full speed and quality.

Accelerating the progress of agricultural science and technology is the key to sustainable agricultural and rural economic development. Precision agricultural technologies (PATs) are technologies aimed at managing in-field heterogeneity (Aubert et al., 2012). As an important commodity grain base and strategic reserve base for grain in China, HRA is striving to develop modernized agriculture as a demonstration area for modernized agriculture. Since 2001, HRA has built a modern agricultural machinery management command and dispatch information system by implementing a pilot project on precision agricultural technologies. Similarly, the project promotes a precision agricultural information system and a GPS navigation wireless mobile network RTK differential system that integrates agricultural machinery information management, command and dispatch, function display, technology training, and management parking. In recent years, the critical technology application of UAV in precision agriculture has achieved good results (Li, 2018). At the same time, due to the development of cultivated land water conservation, soil improvement, and soil conservation technology, the land is concentrated and contiguous through projects such as land remediation and high-standard cultivated land construction. It is more conducive to mechanical operations and improves labor productivity and agricultural production capacity.

5.2 Form of regional differentiation and its origins

Because the different regions differ in topographic and geomorphological characteristics, climatic features, soil types, and crop planting structures, other regions adopt different patterns of green use of cultivated land, which is the subject of ongoing research and has significant regional variability.

In the Northeast of China, the black soil characteristics include black soil, black calcareous soil, white pulp soil, meadow soil, dark brown soil, brown soil, *etc.*, according to the classification of Chinese soil occurrence (Xu et al., 2010). The natural black soil topsoil has high organic matter content, but there are differences in different regions. Different cultivated land conservation measures are adopted for different soil conditions (Han and Li, 2018). This context may be the reason for the differences in the GUL-CL. For example, the black soil layer conservation model in the middle, the thick soil in the central-eastern part of the Songnen, and the meadow soil area in the Sanjiang Plain. Or the black soil layer cultivation model in the erosion area with thin black soil and shallow black soil types such as native light black soil and dark brown loam. The western area of Songnen Plain is a semi-arid region affected by the superposition of water and wind erosion, and soil erosion is severe. The erosion ditch is dense (Yang and Song, 2021). Therefore, a farming technology system with conservation tillage was the core measure that should be adopted.

Qiqihar Branch is in the upper reaches of the Songhua River water system in Heilongjiang Province and attaches importance to the protection of water resources. It establishes fertilization techniques for significant crops and actively promotes organic fertilizers and green pesticides, so these two indicators of the Qiqihar Branch reach the highest value (Zhang et al., 2020). Harbin Branch is the smallest among the nine branches of the HRA, and the farms are relatively scattered. However, the farms are adjacent to cities such as Harbin and Daqing, which have location advantages and agricultural resources. Even though the amount of land that can be cultivated is limited, the efficiency of production per unit of Climate change can alter the regional water cycle and environment to some extent, affecting crop farming systems, cultivated land productivity, and land use types and patterns, which in turn cause changes in the spatial and temporal patterns of cultivated land (Piao et al., 2010; Chen et al., 2012; Newman et al., 2014). Climate warming has contributed to increased cultivated land in northern China, where the temperature is the limiting factor. Climate warming has already driven the boundary of rice cultivation in Heilongjiang Province from 48°N to 52°N to the North, resulting in a gradual increase in the area under rice cultivation (Piao et al., 2010)—a significant expansion of rice cultivation in the Heilongjiang Reclamation Area (Figure 6).

Not only that, during the past 40 years, 80% of the expanded area under rice cultivation was distributed in the Eastern part of the Songnen Plain and the Sanjiang Plain areas, with annual precipitation of less than 500 mm. Moreover, the Songnen Plain has also experienced significant growth in rice cultivation in regions with an annual rainfall of less than 350 mm, with a 22% growth area share (Li et al., 2021). However, the spatial and temporal response of rice area migration characteristics in Northeast China to regional precipitation changes is not closely related (Chen et al., 2016). Such as Jiusan, Harbin, and other branches with low precipitation also carry out “dry to water” projects. In addition, the black soil area soybean plantings will undergo re-expansion in the current “double cycle” new development pattern requirements. Beian, Jiusan, Qiqihar, and other branches are making suitable adjustments to their planting structures by reducing corn and increasing soybeans. However, soybean is a highly water-consuming crop and needs to be supported by corresponding irrigation water resources if higher yield levels are maintained.

In contrast, in 2015, Jiansanjiang started building surface water irrigation projects and took scientific and reasonable steps, like rotating fallow crops and reducing groundwater extraction, which put it at the highest level of water-saving irrigation and surface water replacement groundwater. There are differences in water resource use and other and other aspects among the authorities due to differences in the structure of cultivation (Cui et al., 2020). Subsequent studies on the green use of cultivated land will provide an in-depth discussion of how different cropping structures adopt land conservation.

5.3 Prospects and measures to regulate the cultivated land’s green use

With the strategy of “hiding grain in the land and hiding grain in technology,” the GU-CL is an inevitable trend. In other words, it is a realistic choice for black soil protection. A specific regional model has been implemented and formed in HRA, which can provide some

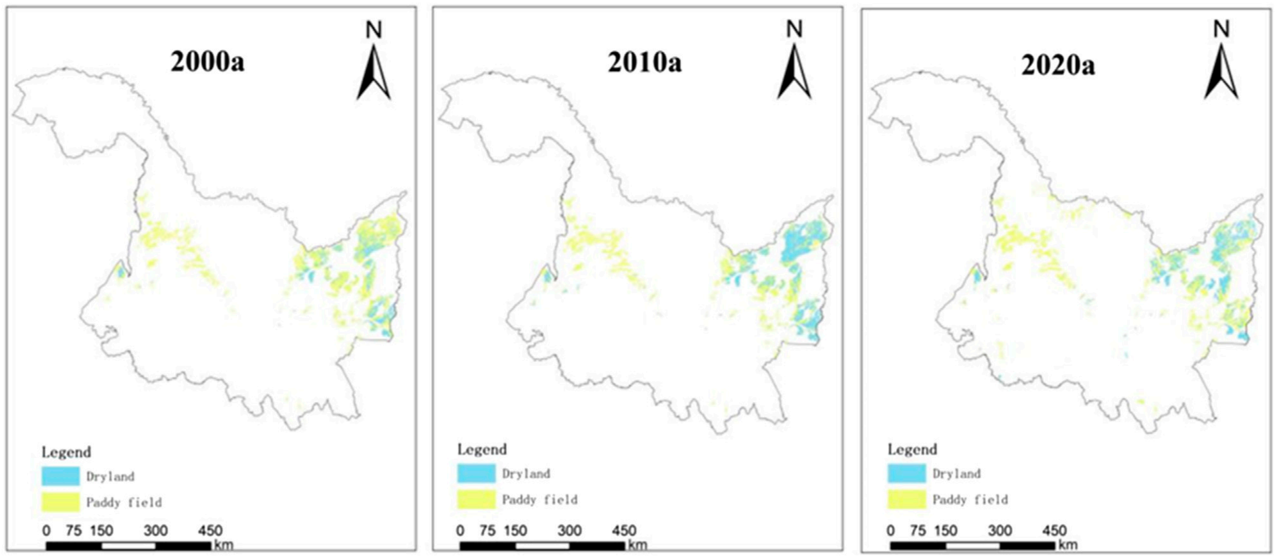

FIGURE 6
2000–2020a Distribution of paddy and dryland in HRA.

reference value for other regions, predominantly rural areas. At the same time, based on the results and analysis, the following suggestions are made.

(1) Develop a differentiated development strategy for the GU-CL based on the reclamation area's economic structure and resource endowment. Sanjiang Plain Reclamation Area needs to be strengthened at an environmental friendliness level. They should accelerate the transformation of farmers' production concepts and promote new plant protection. Then, this strategy will focus on soil testing, formula fertilization, and other agricultural technologies. Reducing the intensity of fertilizer, pesticide, and agricultural film application, promoting agriculture, improving agricultural production quality, and alleviating agricultural surface source pollution are among the strategies they must implement. Songnen Plain Reclamation Area needs to improve energy use efficiency, reduce the intensity of agricultural electricity use, increase agricultural water conservation techniques, and adjust the crop planting structure at the right time.
(2) Strengthen inter-regional synergy, and promote the coupled and coordinated development of cultivated land use. HRA has achieved output efficiency, but environmental friendliness and resource conservation are crucial to promoting GU-CL. Harbin Branch plays a leading role in strengthening the radiation effect of green production technology. Jiansanjiang and Qiqihar Branch, as critical agricultural production areas, promote comprehensive ecological management and take the road of intensive and economic development, which is conducive to the coupling between agricultural development and the environmental environment.
(3) Ecological compensation, as an effective environmental incentive policy, is essential in improving the ecology concern worldwide (Jiang et al., 2022). The government needs to increase financial support for developing and applying new pollution prevention and control technology. Promote land remediation projects to realize a virtuous cycle of ecological management and land resource development. Increase ecological compensation for cultivated land and state transfer payments to make cultivated land in reclamation areas safer for the environment.

Given the authors' research level and data availability, this paper has a few shortcomings. First, the selection of indicators may not be comprehensive enough. Cultivated land utilization is a long-term and complex process involving various aspects. The indicator of cultivated land or system may not fully reflect the connotation of green utilization of cultivated land. Secondly, the one-year data cannot fully reflect the transformation process of green use of cultivated land in the reclamation area, which is not in-depth and comprehensive. In the next step, a more in-depth study can be conducted using consecutive multi-year data to obtain more practical results.

6 Conclusion

In evaluating the single element of GUL-CL, there are obvious differences between different indicators of GUL-CL in the same region, which have certain advantages and disadvantages. The high-level area of GUL-CL is mainly distributed in branches such as Jiansanjiang and Baoquanling in the northern part of the Sanjiang Plain. The low-value area is primarily distributed in branches such as Beian and Harbin. This context leads to significant differences within farms due to the various measures other farms take for the GU-CL and the varying degrees of implementation.

The high-level areas in terms of environmental friendliness are primarily concentrated in the Songnen Plain Reclamation Area. In contrast, at the level of resource conservation, the effect is significant in the Sanjiang plain Reclamation Area, with Jiansanjiang performing exceptionally well. At the level of spatial intensification and output efficiency, the overall development of the HRA is relatively balanced. Land remediation and high-standard farmland construction projects promote the increase of grain production and enhance agricultural production capacity.

Overarchingly, the coupling degree of GU-CL ranges from 0.600 to 0.800, which is a moderately strong coupling. Qiqihar branch is one area in which the GU-CL was significant; therefore, the green utilization system of cultivated land is in a state of mutual feedback, balance, and development. In contrast, the degree of coupling and coordination of GU-CL ranges between 0.200 and 0.500, considered low, and Hongxinglong as an example. Accordingly, the cultivated land green system presented a synergistic resonance development. GU-CL in HRA has ample space for improvement and excellent development potential.

Data availability statement

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

Ethics statement

Ethical review and approval were not required for the study on human participants following the local legislation and institutional requirements.

Author contributions

GD and JX: substantial contributions to conception and design, data acquisition, analysis, and interpretation; GD and JX: drafting the article and revising it critically for important intellectual content; JX: collecting the data. GD, DH, and FY: writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by the National Key R&D Program of China, grant No. 2021YFD1500101.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 30 March 2023
DOI 10.3389/fenvs.2023.1120734

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OPEN ACCESS

EDITED BY
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SPECIALTY SECTION
This article was submitted to Land Use Dynamics,
a section of the journal
Frontiers in Environmental Science

RECEIVED 10 December 2022
ACCEPTED 16 March 2023
PUBLISHED 30 March 2023

CITATION
Xie Z, Fan S, Du S, Zheng Y and Li C (2023), Mechanism, risk, and solution of cultivated land reversion to mountains and abandonment in China.
Front. Environ. Sci. 11:1120734.
doi: 10.3389/fenvs.2023.1120734

Mechanism, risk, and solution of cultivated land reversion to mountains and abandonment in China

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The cultivated land requisition-compensation balance (CLRB) system in China has been designed to defend cultivated land resources and grain production functions. Nevertheless, since the addition of a new policy, namely the linkage of increase and decrease (LID) of urban and rural construction land in 2008, a mass of cultivated land has been returning to mountains, sometimes resulting in abandonment. The county of Wannian was investigated from the microcosmic perspective, and we attempted to analyze the causes and risks employing the boosted regression trees (BRT) model and the grain productive capacity assessment model. The results indicate that (1) The compensatory cultivated land (CCL) has shifted uphill, with considerable fragmentation, from 2010 to 2020, and the abandonment rate reached 14.77%. (2) The factors of site condition, including elevation, patch area, and continuity of cultivated land, as well as a series of combinations, can explain the causes of abandonment. (3) The abandonment of these cultivated land areas eventually resulted in the risk of 297.48 t grain production capacity loss. The reason for the return of cultivated land to the mountains and its subsequent abandonment is the lack of consideration for the coupling relationship among site condition, use state, and function requirement, resulting in a spatial mismatch. Based on the findings, we propose a solution of the natural resources requisition-compensation balance (NRRB). To make up for the loss and reduce the risk, a spatial replacement was taken between the abandoned CCL in uphill and cultivable and available forest land (CAFL) in submontane areas CCL, optimizing the spatial pattern of land use toward Von Thunen's agricultural circle.

KEYWORDS

mountainous area, cultivated land requisition-compensation balance, forest land requisition-compensation balance, cultivated land abandonment, grain production capacity, Wannian county

1 Introduction

Globally, there's a competition for land between the urban expansion and food production (Jiang et al., 2013; Varsha and Paul, 2021). Urbanization usually dominates this competition, resulting in the land relocation for food production to other areas (Jasper et al., 2017). Currently, continuous researches have been conducted on the spatial transfer of cultivated land and its associated environmental and food production risks (Isbell et al., 2019; Halpern et al., 2022). On a large scale, the main part of cultivated land has shifted horizontally to northern inland regions in China, leading to the risk of aridity (Lian et al., 2022; Zhong et al., 2022). However, in mountainous areas, which account for 69.1% of China's total land area, cultivated land has frequently returned to hillsides in recent years. Compared with the trend of population relocation away from mountains, the distribution of arable land shows a seemingly opposite trend, which is a kind of vertically spatial change of arable land, requiring further focus on its mechanism and solution for the resulting risk of grain production capacity loss.

Since the industrial age, urbanization has been driving people out of the mountains, concentrating farming on the plains (Chen et al., 2021; Tan et al., 2021). Abandonment and withdrawal of cultivated land in mountainous areas is an irreversible global phenomenon (Estel et al., 2015; Song and Zhang, 2019). The influencing factors have been summarized from aspects of physical geography, socio-economy, and policy. Previous studies have shown that abandonment and withdrawal are more likely to occur in fragmented areas at higher elevations and with steeper slopes, poor soil conditions, poor field facilities, inconvenient transportation, and far from residential areas (Baumann et al., 2011; Díaz et al., 2011; Shao et al., 2015; Song and Zhang, 2019). The huge opportunity cost gap between agricultural and non-agricultural employment is the most important socio-economic factor that triggers the deagriculturalization of surplus agricultural laborers (Lasanta et al., 2017; Liao et al., 2019; Lark et al., 2020). Policies and systems such as agricultural subsidies and land transfer policies may promote or restrict the abandonment (Ito et al., 2016; Song et al., 2018). With the introduction of policy in China that the construction land in rural areas could be reclaimed into cultivated land and balanced by the reduction of urban cultivated land occupied by construction, this made it possible to reclaim construction land in remote mountainous areas and return cultivated land to the mountains (Liang et al., 2015). Unlike the traditional cultivated land management system in mountains, these new cultivated areas were not reclaimed voluntarily by farmers and, as a result, their characteristics aren't fully understood. A large body of research has focused on the management of reclaimed farmland (Yao et al., 2014; Xin and Li, 2018), but studies on cause analysis and improvement measures for the formation of "unnatural" abandonment are scarce (Liu et al., 2019). It is important to quantify this impact to help policymakers develop reasonable strategies for cultivated land protection and promote sustainable development goals.

The reason and risk for cultivated land abandonment could be explained by the coupling framework of the land use "Condition-State-Function" (Figure 1). In 2008, the concept of land use functions was put forward by the European Union in the Sixth Framework Programme for Sustainability Impact Assessment: Tools for Environmental Social and Effects of Multifunctional Land Use in Europe Regions. This concept was accepted as the private or public products and services provided by different land use states, including economic function, ecologic function, and social function (Helming et al., 2008; Pérez-Soba et al., 2008; Liu et al., 2016). The continuous supply of functions requires the maintenance of a land use status with suitable site conditions. With optimal conditions in terms of light, temperature, precipitation, and soil, natural ecosystems (such as forest land and wetlands) can provide the service of ecological and climate regulation; in contrast, artificial ecosystems (such as industrial land and commercial areas) can provide economic benefits (Mitsuda and Ito, 2011). However, for semi-natural ecosystems (such as cultivated land and gardens), suitable tillage conditions are as important as the continuous and stable input of production factors for system maintenance and function supplement (Foley et al., 2011). Natural suitability, economic feasibility, and social acceptability are considered essential conditions for the maintenance of land use systems (Wang et al., 2016; Li et al., 2020). In turn, the requirement for some ecosystem services provides feedback on the land use state, prompting the generation of corresponding site conditions for

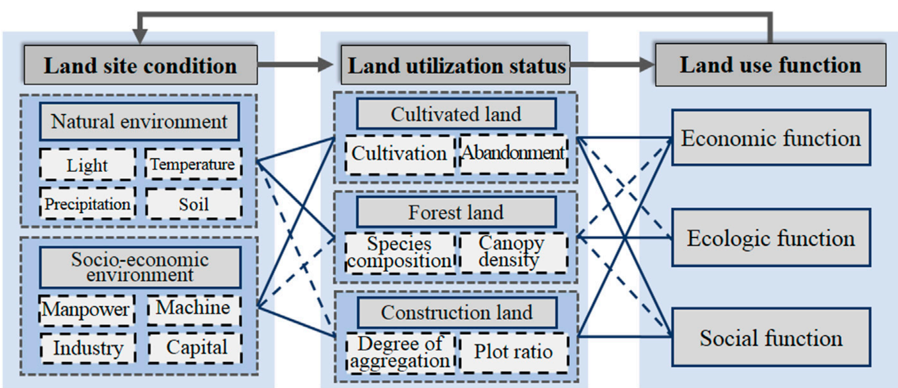

FIGURE 1
The coupling framework of land use "Condition-Status-Function".

maintenance (Wei et al., 2017). In this sense, the spatial matching between land supply and human demand directly determines the sustainability of land use status.

In 1997, the central government of China promoted the "Land Management Law," in which the cultivated land requisition-compensation balance (CLRB) system was proposed formally. At the national level, the CLRB was formulated to take urban development and food demand into account, based on limited land resources. However, at the district level, preferential arrangements were provided for urban development in flat areas, while ignoring the site conditions of cultivated land and the services demanded by farmers in mountainous areas, leading to spatial mismatch. This process is generally overlooked in large-scale studies (Xiong et al., 2020; Chen et al., 2022). The abandonment phenomenon of cultivated land is resulted from its own attributes of resources as well as multi-dimensional interaction between natural geography and social economic environments (Helming et al., 2008; Renwick et al., 2013). The quantity, quality, function and spatial distribution characteristics of fragmentation or scale of the regional land resources themselves are the result of the accumulation of the long-term coupling effects of natural and human factors in the region, which not only is the basis for future land use but also determines the attractiveness level of the additional investment in land use and the ease of land use. It ultimately influences the decision of farmers and herders in the land use (Tian et al., 2023). Although the research of traditional regression model has revealed the effects of single factor on the utilization of cultivated land (Prishchepov et al., 2013; Zhang et al., 2014), it usually fails to explain the mechanisms of multi-factors. Recently, the machine learning has been applied in the multivariate questions, such as the crop yield and food security (Giulia et al., 2022; Balsher et al., 2023), which provides a new method for the research to explain the mechanisms of the abandonment of cultivated land in mountainous areas.

Considering the functional demands of land, a scheme based on NRRB is proposed to resolve the abandonment of CCL. The following questions are answered: 1) What happened in the spatial arrangement and use ratio for cultivated land in mountainous areas under the CLRB system? 2) What is driving the changes? 3) What is the impact of these changes on the regional grain production capacity? Based on the results, we tried to establish an evaluation system of cultivated land reserve resources to screen out CAFL. Furthermore, a spatial optimization plan for the replacement of abandoned CCL in mountainous areas and CAFL in submontane areas is proposed to compensate for the loss of grain production capacity.

2 Background

Almost all countries have formulated laws and regulations to protect cultivated land (Van Vliet, 2019). The role of the CLRB in China is to curb the reckless requisition of cultivated land for urbanization (Sun et al., 2014). Statistics indicate that 200×10^4 hm^2 of cultivated land were compensated due to the CLRB during 2001–2010 (MLR, 2012), largely making up for the loss of cultivated land from construction. However, since 2008, numerous CLRB projects have been implemented with another policy, namely, the linkage of increase and decrease (LID) of urban and rural construction land, compensating the loss of cultivated land by reclaiming rural construction land. The reason for increased number of projects is the joint acquisition of economic and social benefits for local governments. By reclaiming construction land for cultivated, The village collective were able to obtain the economic benefits, and immigrant will would have better living conditions. (Shen et al., 2017; Liu et al., 2019). Statistics show that about 590×10^9 yuan capital has been invested into the countryside since 2012 due to the implementation of the LID (Ye, 2020). However, as a result, cultivated land was shifted from plains to mountainous areas (Li and Hu, 2021), increasing the risk of abandonment.

The ecological environment is another focus for the development of countries now (Yang and Li, 2000; Norse and Ju, 2015). If wetlands, forest lands, grasslands, among others, are converted into construction land and cultivated land, their ecologic functions, such as soil and water conservation, climate regulation, and biodiversity, may be destroyed (Foley et al., 2005; Mamat et al., 2014). The Chinese government prohibits the destruction of the ecological environment during urban construction and the reclamation of cultivated land for agricultural purposes (Shen et al., 2017), exploring the ecological land requisition-compensation balance (Song et al., 2015; Zhang et al., 2015). The forest land requisition-compensation balance in China has gone through two stages. The first stage is the quantitative balance, that is, the area of compensatory forest land shall not be less than that of the requisitioned forest land. The second stage is total quantity control, that is, the conversion of forest land to non-forest land needs to be strictly restricted, and ensuring the amount of forest land occupation is controlled, with the aim to maintain the forest areas. Compared with the CLRB, the intensity of the management of the forest land requisition-compensation balance tends to tighten. This has brought local governments to a standstill in dealing with land disputes for urban construction, cultivated land replenishment, and environmental protection. By contrast, it appears more flexible to the wetland mitigation bank system in the United States and the eco-account system in Germany (Kaplowitz et al., 2005; Pröbstl-Haider and Ammer, 2017). To avoid losses of ecological land and to maintain the ecological value, they require that ecological land should be newly built, restored, conserved, or enhanced in another area before the former ecological land is occupied.

3 Methodology

3.1 Study Area

Wannian County (28°30′15″-28°54′5″N, 116°46′48′-117°15′10″E) is located in the west of the central part of Shangrao City, Jiangxi Province, China (Figure 2). It is an important area of the Poyang Lake Plain, which is one of the nine major commodity grain bases in the country. A high grain production is therefore of great significance to China's food security. The terrain is mostly mountainous, high in the southeast and low in the northwest, and known as "six mountains, one water, and two penny cultivated land." About 58.5% of cultivated land is distributed on the hills and gentle slopes on both sides of the river; forest land is

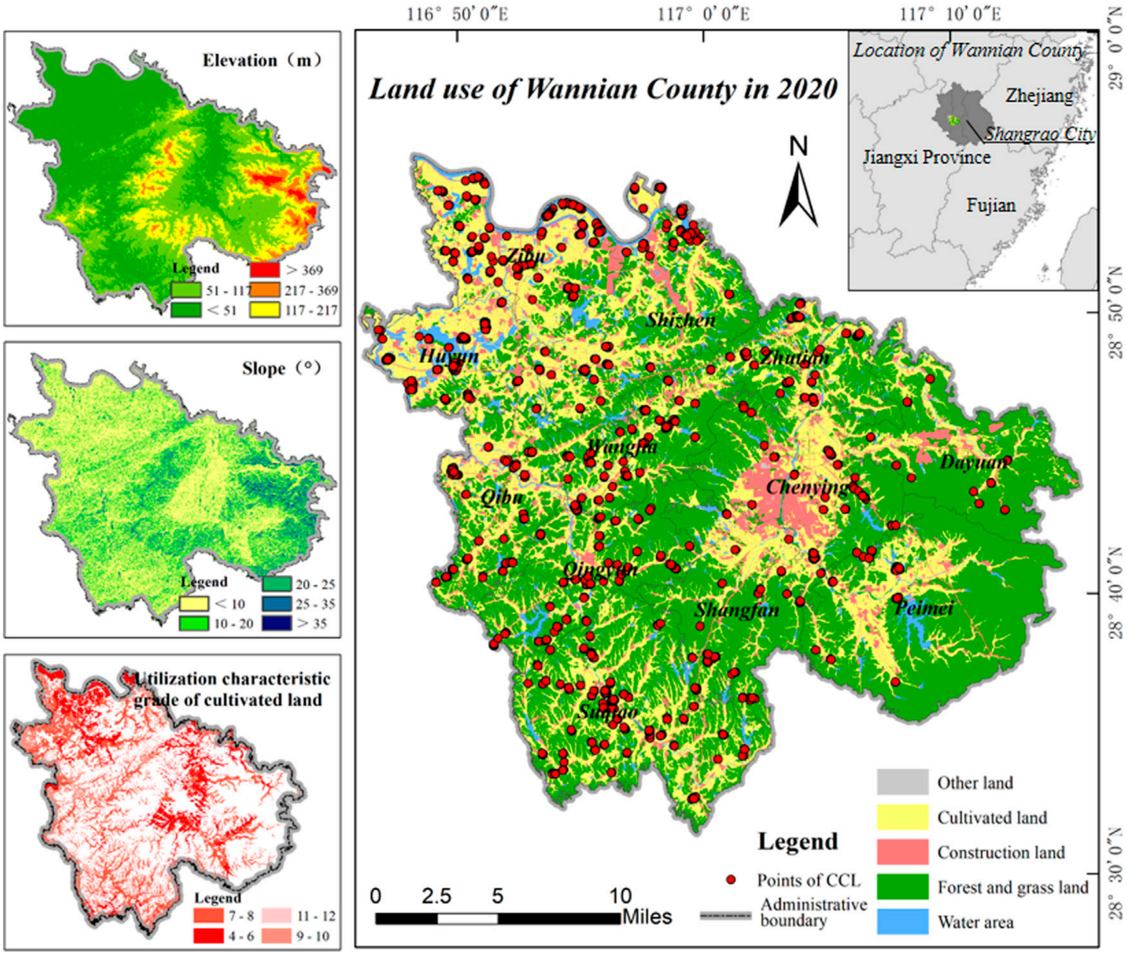

FIGURE 2
The geographic locations of the study area.

widely distributed in the territory, reaching a coverage of 64.1%. Most rural settlements are distributed in river valleys in hilly areas, and some are dispersed in mountainous areas. The climate is subtropical monsoon humid climate, with an annual average temperature of 17.4°C and a precipitation of 1,808.0 mm, facilitating abundant crop and natural vegetation growth. Siltstone is the main soil parent material; under the prevailing climatic conditions, it is easily reclaimed to cultivated land.

3.2 Research framework and data source

Figure 3 presented our research framework, and it included four main steps: 1) Identifying the distribution and use situation of CCL: Land use datasets in 2020 were obtained through remote sensing interpretation technology, including residential land, transportation land, cultivated land, and forest land; the forest land was divided into dense, sparse, and other forest land, based on canopy density. The CCL presented as forest land in 2020 were then identified as abandonment, based on the LID spatial data. 2) Machine learning statistical model of boosted regression trees was utilized to analyze the driving factors of abandonment: Based on the data of permanent population, elevation, slope and cultivated land quality, etc., three first-level indicators of physical-geographical environment, socio-demographic environment and attitude of resource endowment were characterized, and used as independent variables, while the condition of CCL was taken as the dependent variable. 3) Constructing the CAFL replacement evaluation system: Based on the analysis results of the driving factors of arable land abandonment, the evaluation index Chinese Cultivated land Reserve Resources Investigation and Evaluation was optimized. 4) Risk Comparison of grain production capacity loss: Based on the data of cultivated land quality, the grain productive capacity assessment model was utilized to estimate the differences in the loss of regional grain productivity capacity under the three scenarios: pre-LID, post-LID, and post-NRRB. It should be noted that the agricultural quality grade of CAFL was assigned as that of cultivated land nearby. The main data sources used in this study are listed in Table 1.

3.3 Boosted regression trees (BRT)

BRT, the machine learning statistical model, has been widely used in the mechanism research of environmental change. Compared to traditional statistical model, a BRT model easily

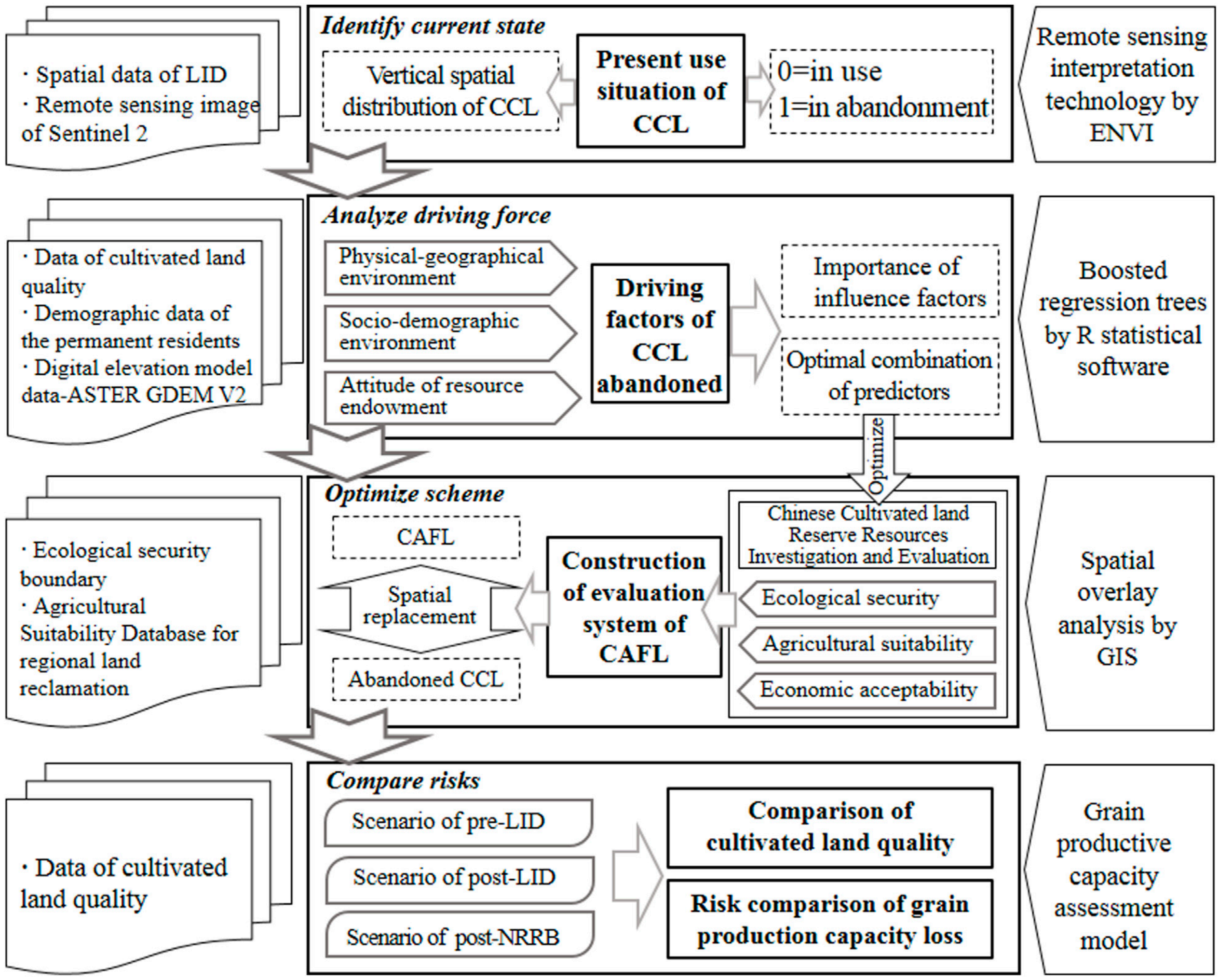

FIGURE 3
Research framework.

captures complex and non-linear relationships (Li and Hu, 2021). It can capture the importance and marginal effect of independent variables. The importance can quantify the contribution of each independent variable, and the marginal effect shows the potential impact of independent variables as their magnitudes vary (Elith et al., 2008). The model was performed in R statistical software by using the gbm package with a "bernoulli" distribution.

3.3.1 Parameter settings

Four parameters require to be specified are tree complexity (TC), learning rate (LR), number of trees (NT), and bagging fraction (BF). TC determines the number of nodes in each tree and controls the interaction level. LR represents the contribution of each tree to the final model. NT relies on a combination of TC and LR and is recommended for sizes larger than 1,000. BF sets the proportion of randomly selected data used for model training and validation. Given our relatively small sampling dataset, BF was set at 0.50 (Soykan et al., 2014) while TC was set at 5 as suggested by Elith et al. (2008). LR and BF are set to 0.001 and 0.70, respectively. The BRT model obtained the highest coefficient of determination (R2) with the optimal NT in the range of 2,000–10,000 was considered as given the optimal parameter settings.

3.3.2 Importance of influence factors on CCL abandonment

The relative importance (or contribution) of each variable can be measured based on the number of times the variable is selected for splitting, weighted by the squared improvement to the model, and averaged over all trees (Friedman, 2001). As the specific site conditions of cultivated land, physico-geographical environment, socio-demographic environment, and resource endowment attributes were identified as the three types of variables that may affect the "natural" abandonment of cultivated land. The corresponding influence factors were obtained from previous studies, the specific indicators were determined (Table 2).

3.3.3 Determining optimal combination of influence factors

The optimal combination of influence factors used for spatial prediction of CAFL is determined by a variable selection approach

TABLE 1 Main data sources.

Name	Date	Data sources	Supplementary instruction
Spatial data of LID	2010–2019	Bureau of Natural Resources and Planning in Wannian County	The database includes the spatial location and area of CCL for each year
Data of cultivated land quality	2018	The Agricultural Land Classification and Gradation Project	The database comprehensively analyzes the grades of natural properties, use characteristics, and the economic input-output of cultivated land
Remote sensing image of Sentinel 2	2020	The European Space Agency Copernicus Open Access Hub (https://scihub.copernicus.eu/)	Google Earth images were selected to supervise the accuracy of the interpretation results; the Kappa coefficient reached 0.94, meeting the interpretation accuracy requirements
Demographic data of the permanent residents	2019	Questionnaire survey of 1,268 unincorporated villages	–
Digital elevation model data-ASTER GDEM V2	–	The geospatial data cloud platform of the Chinese Academy of Sciences (http://www.gscloud.cn/)	From this data, the slope and aspect data was further calculated
Ecological security boundary	–	Bureau of Natural Resources and Planning in Wannian County	Ecological security refers to the necessity to avoid some land with important ecological value or prone to land degradation and geological disasters outside the ecological red line
Agricultural Suitability Database for regional land reclamation	–	Bureau of Natural Resources and Planning in Wannian County	Agricultural suitability refers to suitable cultivated conditions of topography, temperature, precipitation, and soil for agricultural production (Mondal and Basu, 2009; Passioura, 2006). In especial, The soil condition is the main factor to the use of cultivated land, including soil thickness, surface soil texture, soil parent material, soil pH, soil contamination, among others (Ochola and Kerkides, 2004; Rahmanipour et al., 2014)

based on the BRT algorithm, which is performed in two steps. First, a BRT model is used to calculate the relative importance of all 10 variables. Pearson correlation analysis was then performed to eliminate redundant variables. Second, a BRT algorithm-based backward selection approach was performed to select the optimal number of variables by eliminating the least important variable step by step: 1) a BRT model was built to rank the non-redundant variables; 2) the least important variable was eliminated; 3) the retained variables were used to build a new BRT model and their importance was re-ranked. The optimal number of variables was determined by the highest coefficient of determination (R2) among these BRT models.

3.4 Grain productive capacity assessment model

The actual grain yield isn't only affected by the quality factors of cultivated land but also restricted by the regional agricultural input and agricultural technology management (Xie et al., 2017). The grain productive capacity refers to the highest yield of a fine crop variety per unit area that might be obtained assuming all or part of the production factors are in the optimum state, not considering agricultural input and agricultural technology management; the value is higher than the actual grain yield. Therefore, the light-temperature (climatic) productivity potential index was set as the starting point for calculations. Soil, site, plot, and agricultural infrastructure conditions were considered individually, based on their influence on the productivity potential (Jiang et al., 2017). The calculation formula is as follows:

$$I_{LPPi} = a_i \times \left[\left(\sum_{j=1}^{n} Fs_{ij} \times Ws_{ij} + \sum_{j=1}^{n} Fi_{ij} \times Wi_{ij} \right) \times \prod_{j=1}^{n} Fp_{ij} \times \prod_{j=1}^{n} Fa_{ij} \right] \times \beta_i \quad (5)$$

Where I_{LPPi} denotes the cultivated land productivity potential of plot i; a_i represents the light-temperature (climatic) productive potential; Fs_{ij} and Ws_{ij} are the score and weight of the soil condition indicator j of plot i, respectively; Fi_{ij} and Wi_{ij} are the score and weight of site condition indicator j of plot i, respectively; Fp_{ij} is the score of the plot character indicator j of plot i; Fa_{ij} is the score of the agricultural infrastructure condition indicator j of plot i; and βi is the production ratio coefficient. The Regulation for the Gradation and Classification of Agricultural Land Quality stipulates that β_i is the rate of the base crop maximum yield and another appointed crop maximum yield.

4 Results

4.1 Distribution characteristic of compensation cultivated land

From 2010 to 2020, the total area of CCL in Wannian County reached about 232.47 hm^2 in the scenario of post-LID. The CCL reclamation mainly occurred from 2011 to 2012 and 2017 to 2019, with no reclamation in 2014 and 2015. The average elevation of

TABLE 2 The definition and description of the variables of factors influencing CCL abandonment.

Types of variables	Codes of indicators	Names of indicators	Definitions and assignments of variables
Dependent variable	y	Condition of CCL	0 = in use; 1 = in abandonment
Physical-geographical environment	x_1	Elevation	Assess the elevation (unit: m)
	x_2	Slope	Assess the slope (unit: °)
	x_3	Aspect	0 = flat (0°)
			1 = shady (0°–45°、315°–360°)
			2 = semi-shady (45°–135°)
			3 = semi-sunny (225°–315°)
			4 = sunny (135°–225°)
Socio-demographic environment	x_4	Traffic distance to adjacent residential area	Calculate and assess the traffic distance to the nearest residential area according to the road accessibility (unit: m)
	x_5	Traffic distance to adjacent cultivated land	Calculate and assess the traffic distance to nearest cultivated land according to the road accessibility (unit: m)
	x_6	Resident population density of the village	Resident population (unit: person/km^2)/total area of the village (unit: km^2)
Attitude of resource endowment	x_7	Grade of natural quality	The natural quality is a benchmark crop yield index converted by the yield ratio coefficient, which can be obtained in accordance with the local standard farming system under certain natural environmental conditions of light, temperature, water, and soil
	x_8	Grade of use situation	The use situation is the sum of the benchmark crop yields converted by the yield ratio coefficient under the natural environmental conditions and average tillage intensity
	x_9	Grade of economic benefit	The economic benefit is the economic return index of cultivated land management, obtained by revising the economic coefficient based on the index of the use situation
	x_{10}	Patch area	Total area of the cultivated land patch (unit: hm^2)

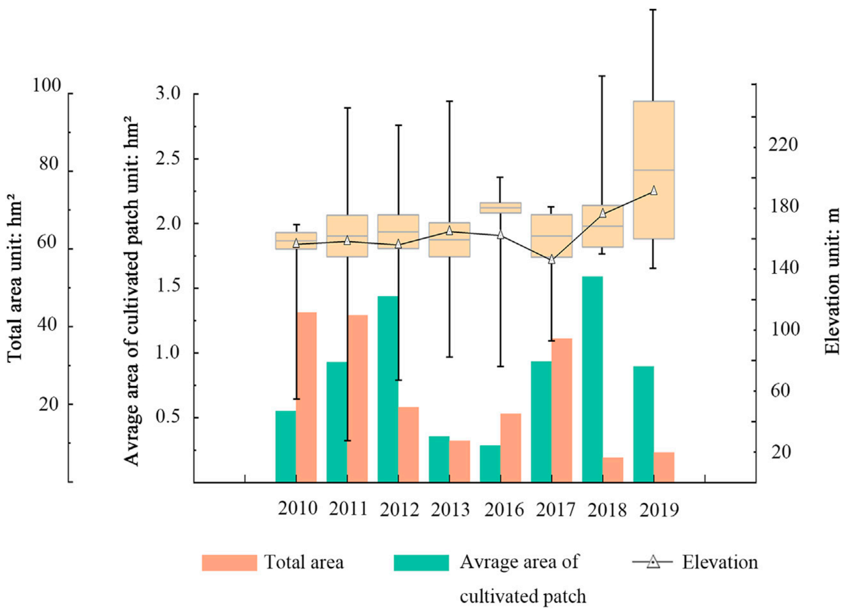

FIGURE 4
Statistics on the area and elevation of CCL by LID projects from 2010 to 2019 in Wannian County.

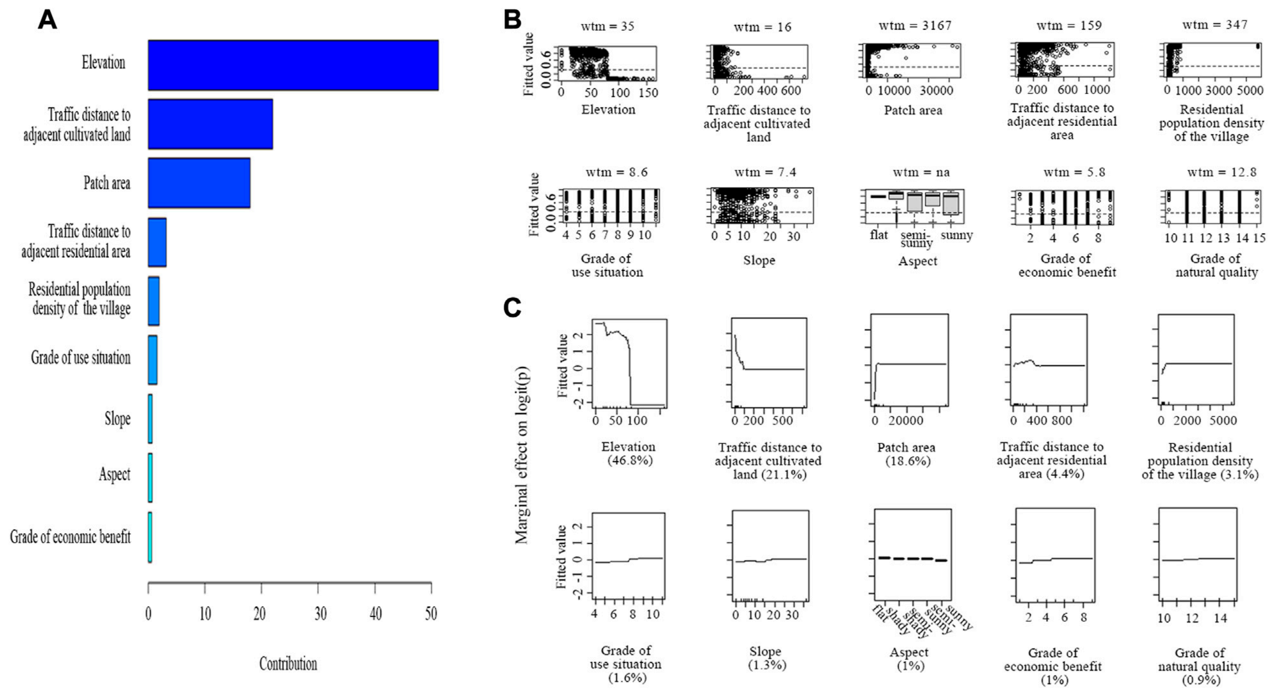

FIGURE 5
Influence of main driving factors of CCL abandonment. **(A)** Contributions (%) of influence factors on CCL abandonment. **(B)** Distribution of CCL in each explanatory variable. **(C)** Marginal effects of the most important explanatory variables.

reclaimed land fluctuated upward from 154.71 m in 2010 to 192.47 m in 2019 (Figure 4), much higher than 50.70 m, the same figure of cultivated land of county-level in the basic years. Further analysis of annual variations of the elevation distribution of CCL demonstrated that the median of the average elevation of CCL had a gentle trend to climb up. To be more specific, it went up from 26 m, the lowest value in 2011 to 146 m, and the highest value in 2018. Moreover, the peak value went up from 169.5 m in 2011 to 290 m in 2019. In the aspect of upper and lower quartiles, this figure gradually tended to reach the highest value, deviating from the median (Figure 4). It can be seen that the height of CCL showed a trend to climb up. Considering the number of patches of compensatory land, we can find that the average patch area of CCL decreased from 1.31 hm^2 in 2010 to 0.19 hm^2 in 2018 through the analysis. Therefore, the next conclusion can be drawn that the CCL showed a trend to be fragmented gradually.

4.2 Analysis of the reasons for the abandonment

According to statistics, the abandoned area of the CCL was 34.34 hm^2, accounting for 14.77% of the total area. Based on the BRT model, the relative contributions of the influence factors to the CCL abandonment are presented in Figure 5A. The dominant indicators influencing the CCL abandonment were the elevation (x_1), traffic distance to adjacent cultivated land (x_5), and patch area (x_{10}), with 51.28%, 22.00%, and 18.00% contribution rate, respectively. The marginal effects were further analyzed and are shown in Figures 5B, C. When the elevation is below 80 m or traffic distance to adjacent cultivated land is below 100 m, it showed a positive correlation with the CCL abandonment, demonstrating that the higher the elevation or the greater the distance is, the easier CCL is to be abandoned. In contrast, a negative correlation with the CCL abandonment was observed for the patch area below 0.12 hm^2, which tells us that the larger the area of CCL is, the less likely it is to be abandoned. However, at elevation above 80 m, it showed a negative correlation with the CCL abandonment, which cannot be explained by a marginal correlation of a single factor.

Further pairwise interaction effects between the influence factors were determined in Figure 6A. The cultivated land use showed obvious differences only in these situations: x_1-x_{10}, x_1-x_5, x_5-x_{10}. The pairwise interaction effects on the CCL abandonment was represented in three-dimensional partial dependence plots (Figure 6B). To be more specific, when it comes to these three situations, ① $x_1 > 80m \cap x_{10} < 0.12\ hm^2$, ② $x_1 > 80\ m \cap x_5 > 75\ m$, ③ $x_5 > 75\ m \cap x_{10} < 0.12\ hm^2$, the general trend of abandonment can be seen clearly. To sum up, the possibility of CCL abandonment is higher in these four situations, and it will decrease on the contrary.

4.3 Construction of the evaluation system of CAFL

According to the Chinese system of "Technical Program of National Cultivated land Reserve Resources Investigation and Evaluation," the main evaluation contents of suitable cultivated land include ecological security and agricultural suitability. These are some of the direct site condition factors of crop growth from the

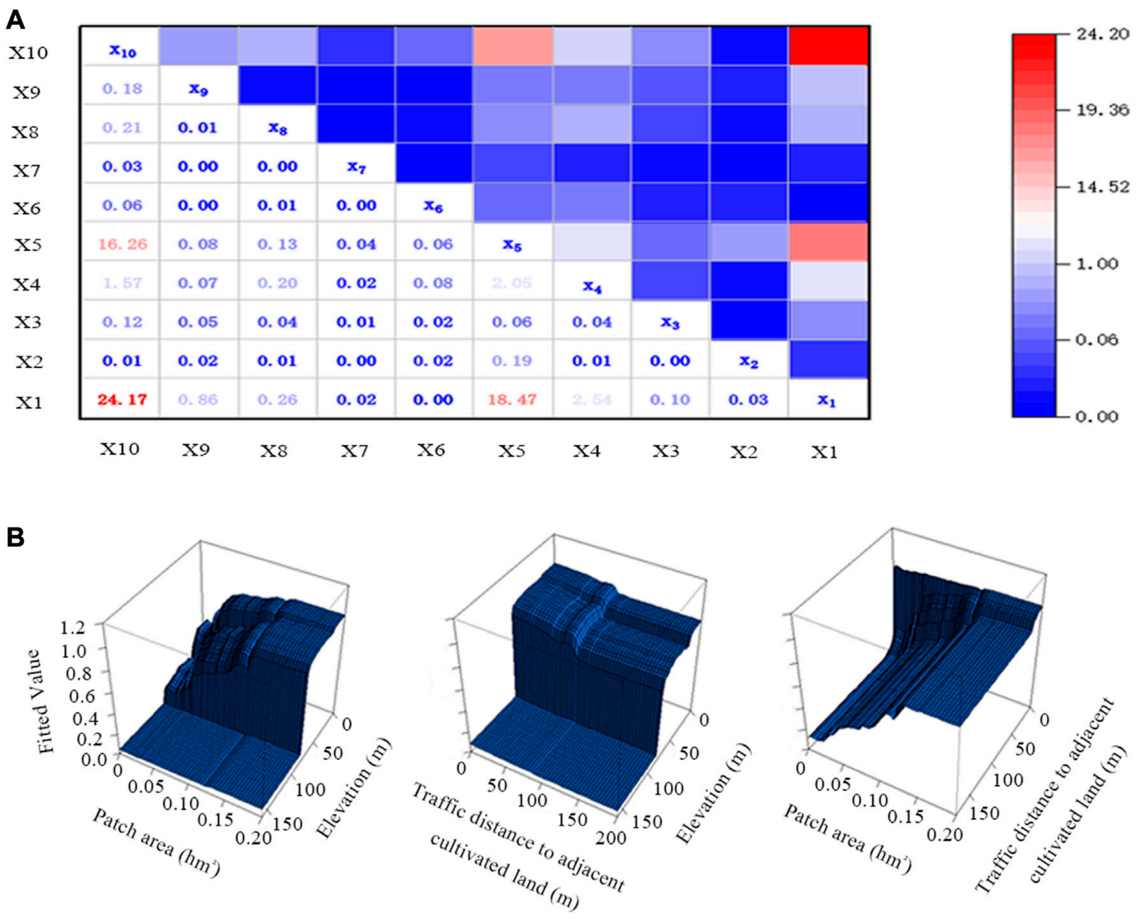

FIGURE 6
The optimal combination of influence factors on CCL abandonment. **(A)** The contributions of pairwise interaction effects on CF abandonment. **(B)** Three-dimensional partial dependence plots representing the pairwise interaction effects between the most important variables.

theoretical perspective. According to the coupling framework of land use "Condition-Status-Function" sustainable land use must also be matched with functional demand. As shown in the analysis of reasons for abandonment, elevation, traffic distance to adjacent cultivated land, and patch area are indirect factors for the sustainable use of cultivated land. So the research results were taken as the indicators of farming convenience, representing the economic acceptability. Finally, the evaluation system of cultivated land reserve resources suitable for reclamation and use is established (Table 3). The minimum limiting factor method was adopted to comprehensively evaluate the forest land in the study area. That is, only if all requirements are met, the one can be considered as CAFL, and as the replaced target for abandoned CCL.

The evaluation results show that the area of the CAFL in Wannian County is about 3,183.39 hm^2, with a dense forest area of 2,809.26 hm^2, accounting for 88.25%. The areas of sparse and other forest land are 63.98 and 310.15 hm^2, respectively, accounting for 2.01% and 9.74%. As seen in Figure 7, the CAFL is mainly distributed in Zibu Town, Shizhen Town, and Huyun Township, with a flat terrain in the northwest. Among them, dense forest land is mainly distributed in Shizhen Town, Zibu Town, and Huyun Township, whereas other forest land can be mainly found in Suqiao Township, Shizhen Town, and Huyun Township and sparse forest land in Peimei Town, Dayuan Town, and Zhutian Township.

4.4 Grain production capacity loss in different scenarios

According to the statistics of cultivated land quality, the grade of natural quality, use situation, economic benefit of the cultivated land in Wannian County were divided into 3 categories, the high level (4–7), the medium level (8–10) and the low level (11–13). As shown in Figures 8A, B, the area weighted average of the natural quality of cultivated land in the whole area is 9.27 grade, and that of the use situation one and economic benefit ones are 7.32 grade and 8.36 grade, respectively. By contrast, the area weighted average of the natural quality of the CCL for LID is 9.26 grade, and that of the use situation one and economic benefit ones are 7.47 grade and 8.78 grade, partly. The average quality is lower than that of the cultivated land in the whole county. As shown in Figure 8C, for the abandon one of the CCL, the weighted average value for area of the natural quality is 9.49 grade, and that of the use situation and economic benefit ones are 8.5 grade and 9.25 grade, therefore, the

TABLE 3 The index system for evaluating cultivated land reserve resources in Wannian County.

Dimension	Indicators for evaluation	Requirements for farming conditions	Explaining
Ecological security	Conditions of ecology	The locations are out of the ecological red lines and the development activities here will not result in land degradation or geological disasters	Excluding: ①nature reserves, parks, drinking water sources and tidal flats with an area ≥100 hm^2; ②Ecologically fragile area; ③land where geological disasters such as collapse, landslide, debris flow, ground collapse, ground fissure and land subsidence frequently occur; ④Flood storage and detention area
Agricultural suitability	Terrain and slope	Slope ≤25°	The land whose slope ≥25° is prohibited from being cultivated according to the stipulation in China
	Accumulated temperature	The annual accumulated temperature above 10°C ≥ 1800°C	Located in the middle and lower reaches of the Yangtze River, the Wannian County is in the tropics and subtropics without high mountains and limit for temperature
	Annual amount of precipitation and conditions of irrigation	Annual precipitation ≥400 mm or irrigation conditions can meet the requirement	The climate type of Wannian County is subtropical monsoon humid climate, whose annual average amount of precipitation is about 1908.4 mm so that the limit for irrigation doesn't exit
	Soil texture	The soil texture is loamy, clayey or sandy	If lots of gravels exit in soil, they will not only result in serious water and fertilizer leakage, but also affect crops to take root. Even if the irrigation conditions can meet the requirement, the land is not suitable for farming because of large leakage
	Condition of soil contamination	The amount of soil contamination = 0 or doesn't exceed the national standard	The land whose amount of contamination exceeds the national standard is not suitable to be cultivated land reserve resources
	Degree of salinity	The degree of soil salinization is less than the level of severity	The content of salt in soil will affect the growth of crops when the salinization degree comes to the level of severity
	Conditions of drainage	Drainage conditions can meet the requirement	It means that the land can drain off water by itself or is suitable for construction of drainage system
	Thickness of soil and conditions of its parent material	The thickness of soil layer ≥30 cm, or its bedrock can be weathered, or it has foreign soil sources	In the southern humid area, the land can be reclaimed as long as its underlying bedrock is easily to be weathered and thickness ≥30 cm. The siltstone that can be easily weathered is widely distributed in Wannian County, which can become soil with water-retaining property and permeability through certain engineering measures
	pH value of soil	4.0 < pH < 9.5	It's quite difficult for crops to be cultivated in the alkaline soil whose pH ≥ 9.5 and acid sulphate soil whose pH ≤ 4.0 unless we modify the soil with chemical method. However, it is too hard and costs a lot
Economic acceptability	Convenience of farming	Elevation ≤80 m ∩ patch area ≥0.12 hm^2 ∩Traffic distance to adjacent cultivated land ≤75 m	The convenience of cultivation reflects the economic feasibility, and affects whether the cultivated land is used or not after being reclaimed

average quality of the abandon one of the CCL is even lower. Next, the total grain production capacity loss caused by the CCL abandonment after LID was calculated with the calculation formula of grain production capacity 5), which was 297.48 t.

In the scenario of post-NRRB, the area-weighted average of the natural quality of the cultivated land reclaimed from CAFL was 9.45 grade, whereas the values for the use situation ones and economic benefit ones were 7.94 grade and 9.26 grade, respectively (Figure 8D). These levels are slightly lower than that of the cultivated land in the entire county but it is still slightly higher than that of abandoned CCL. With the grain productive capacity assessment, it was calculated that about 38,498.84 t of grain production capacity would be obtained in the whole county by reclaiming the CAFL, including 33,910.67 t from dense forest land, 651.30 t from sparse forest land, and 3,936.87 t from other forest land, accounting for 88.08%, 1.69%, and 10.23% of the total, respectively. The loss of 297.48 t of grain production capacity from abandoned CCL in mountains, accounting for 12.5% of the regional total, can be made up only by replacing and reclaiming the sparse forest land in suburbs.

5 Discussion

5.1 Results comparison and interpretation of reasons for the abandonment

Since the mid-20th century, the rate of conversion of natural ecosystem to cultivated land has increased rapidly (Ramankutty and

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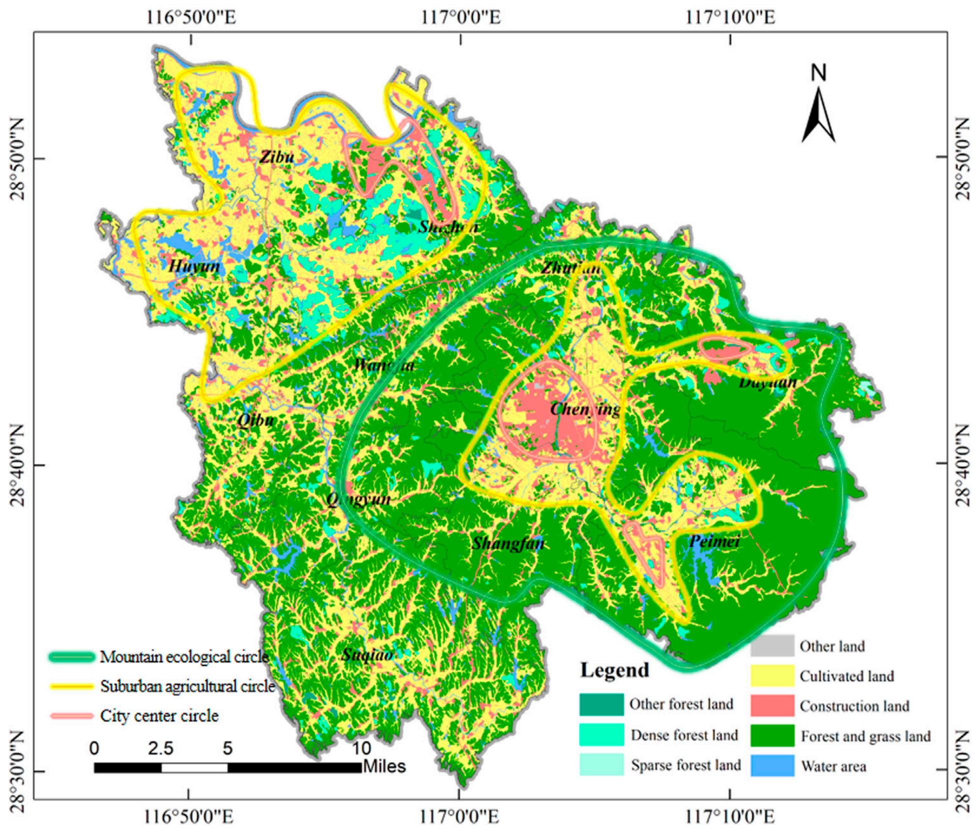

FIGURE 7
The distribution of CAFL in Wannian County.

Foley, 1999) while abandonment is also happening. Estimates suggest that approximately $1.5 \times 106\ \text{km}^2$ of cropland was abandoned globally between 1700 and 1990 (Ramankutty and Foley, 1999). We found that over the past decade, China's mountainous regions have been undergoing cultivated land reclamation at the same time as abandonment, but with the difference that the new cultivated land comes mainly from the abandoned artificial ecosystem, namely, rural settlements, followed by new abandonment. Old abandonment in the mountains often occurs where natural conditions are unfavourable to agriculture (Hinojosa et al., 2016). Factors contributing to unfavourable agricultural suitability include land fertility (Alix-Garcia et al., 2012), altitude (Yang et al., 2019), soil erosion (Pepe et al., 2019), and climate change (Lambin et al., 2003). The external causes in the national market economy, which caused the emigration of the young population to work in the cities and the importation of goods that were formerly produced in the mountains (Lasanta et al., 2017). Xu et al. (2019) note that agricultural abandonment is generally driven by rural–urban migration, where better economic opportunities can be found. Our research results show that new abandonment is not related to agricultural suitability such as cultivated land quality, slope and aspect, but rather to its altitude, distance to adjacent cultivated land and patch area. The reason is that the unit land and labor economic output rates of scattered cultivated land are very limited, which makes agricultural suitability no longer the primary reference factor for cultivated land use. The Chinese government is offering compensation for large-scale grain production, through which farmers can receive more subsidies to boost labor productivity. This makes the realization of large-scale agricultural production become the primary basis of cultivated land use.

The cause of new abandonment in mountainous is not a single factor, but a complex multi-factor problem, namely, the inefficient space allocation caused by the implementation of CLRB, without fully considering the coupling relationship among land site conditions, land use status, and land function requirements. Land marginalization due to unsatisfactory land suitability and reduced economic viability is the root cause of cropland abandonment (Lasanta et al., 2017). According to Von Thunen's agricultural location theory, the space allocation of agricultural land is mainly determined by the transportation cost, with the influence factors of freight, distance, and item weight, forming a concentric structure dominated by a certain crop in a certain circle (Figure 9). In the process of industrialization and urbanization, humans in the mountainous agro-ecosystems have gradually immigrated out of the remote mountains, either actively or passively (Ramankutty and Foley, 1999; Chen et al., 2022). The demand degree of agricultural production in the original location decreased significantly for the immigrant farmers, whereas in the suburban areas in submontane regions, with a flat terrain, a high soil thickness, and agminated immigrants, the demand for land for cultivation increases (Lasanta et al., 2017). A recent review 276 households on the Loess Plateau

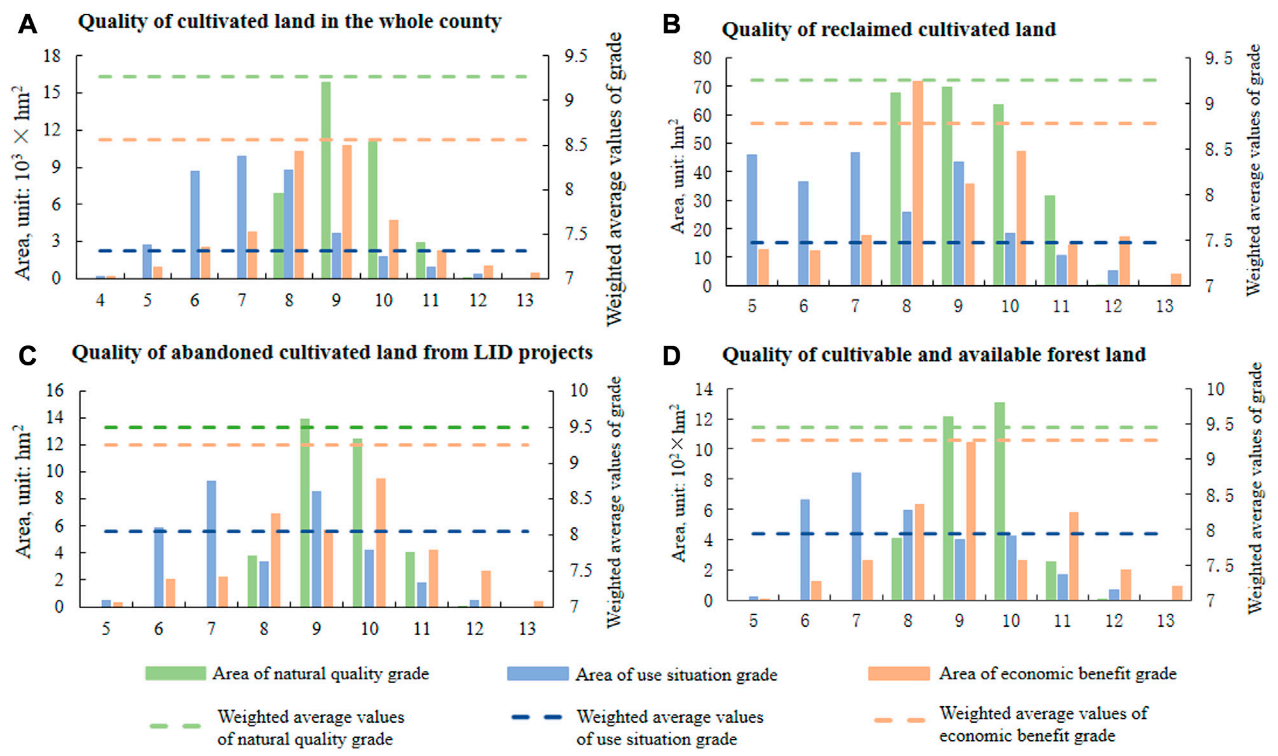

FIGURE 8
The quality of various types of cultivated land of Wannian County in different scenarios. **(A)** Quality of cultivated land in the whole county. **(B)** Quality of reclaimed cultivated land. **(C)** Quality of abandoned land from LID projects. **(D)** Quality of cultivable and available forest land.

found that farmers are unwilling to cultivate steep slopes or to employ recultivation on restored land due to the greater distance costs and lower grain yields when vegetation restoration programs don't affect grain self-sufficiency (Wu et al., 2021). While compared to arable land, forest land provides mainly ecological but not economic functions for humans due to China's forest protection policies (Mayer et al., 2005; Stahls et al., 2010). The provision of the ecological function, however, is independent of the transportation cost and is realized *via* telecoupling (Li et al., 2023).

5.2 Improvement scheme for requisition-compensation balance

A broader approach in regions faced with land abandonment includes the consideration of the economic acceptability (human, natural, etc.) available to foster rural development beyond a sole focus on agricultural production (Zeng et al., 2022; Alan et al., 2013). If the land cannot supply economic function needed and there are significant benefits to the environment of land abandonment it may be unwise to concentrate policies on maintaining agricultural use (Alexander et al., 2013). Regional and local land use planning and polices provided for changing the structure of farms will affect the process of land abandonment (Alan et al., 2013). According to Von Thunen's theory and realistic demands, the matching of functional requirements considered further that construction land is required in the city center circle, and cultivated land and forest land are required in suburban agricultural circle and mountain ecological circle, respectively (Figure 7). Therefore, we propose to establish the NRRB scheme for rational spatial replacement among cultivated land, forest land, and construction land. The goal is to make various natural resources maintain their sustainable use and perform effective functions.

In 2018, the responsibilities of forest and grass land, cultivated land, and construction land were consolidated under the administration Ministry of Natural Resources, providing administrative guarantees for the coordinated management of the three types of land. Based on the research results of economic acceptability in this paper, it is possible to assess and screen out the rural construction land with a high probability of being abandoned after reclamation. When cultivated land in cities is occupied by construction, the construction land in remote rural mountains could be restored to forest and grass land, integrating with the surrounding green environment. At the same time, CAFL in migration destinations should be selected and reclaimed as a supplement to the cultivated land occupied in cities, in accordance with the criteria of grain production capacity balance. Cultivated land is given priority over forested land in spatial arrangements due to stricter usage conditions and more pressing requirements for grain production. The NRRB scheme can ensure that all types of land are used effectively, perform their functions and avoid loss of regional food production capacity.

5.3 Implications and shortcomings

Vegetation restoration strategies adapted to local conditions can reduce the risk of grain shortage for 9.30–11.97 million farmers and

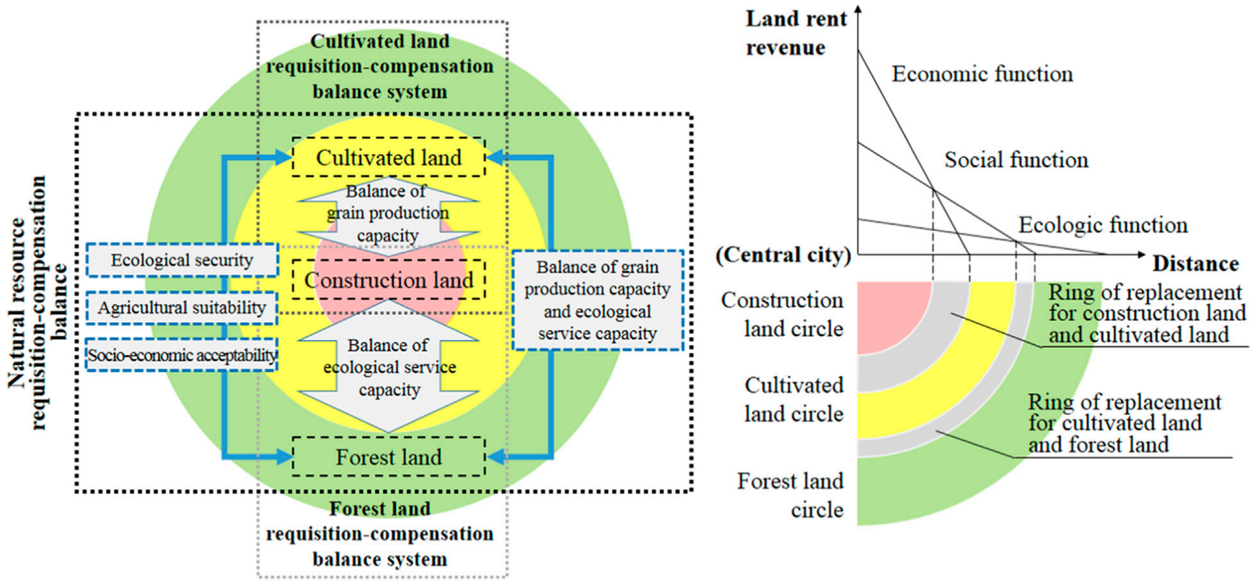

FIGURE 9
The scheme of land use space optimization. Note: For the same land use service, the land rent revenue declines as the increase of the distance from the central city results in higher freight costs. It can be the marginal demand when coming to 0 since this condition is not economically reasonable even if the site condition makes sense. The line connecting the point of central city (freight = 0) and that of marginal demand is called "the curve of rent." Each kind of land use function has its own curve, whose slope is dependent on the rate of freight. Therefore, the slope will be higher if the function is hard to be transported while being lower on the contrary. Since it is an economic rational activity aiming at maximizing land rent income, the inner rings of the cultivated land and forest land concentric circles are the most suitable districts for the expansion of land economic and society functions respectively, and the mountain area farthest from the central city becomes that for the development of forest due to its lowest freight rate of ecological function.

contribute to a more balanced development and the sustainability of vegetation restoration in mountainous areas (Zeng et al., 2022). Therefore, the CLRB system needs to be more elaborately designed when involved in the trade-offs between green and grain; this would help to make up for the loss of regional grain production capacity caused by the CLRB system. Meanwhile, it promotes the formation of land use patterns for efficient agricultural use due to compliance with Von Thunen's agricultural location theory. However, although achieving the quantitative balance, the volume and ecological service capacity of compensatory forest land aren't balanced to occupied one, and the loss is difficult to make up in the short term. Limited by the length of the article, we didn't calculate the loss amount of service capacity and didn't analyze the required time. However, in the tropical and subtropical regions of southern China, the main mountainous areas of China and with abundant rain and heat, it can be restored to shrub forests in a short period of time and to arbor forests with a certain degree of canopy density after several years (Ashton and Zhu, 2020). The historical observation by Google Earth provides evidence that the average canopy closure of abandoned CCL in the study area reached 43% after 5 years without intervention. On the other hand, the ecological regulation service for forest land mainly includes soil and water conservation, carbon fixation, and biodiversity. Studies on soil and water conservation have shown that abandoned cultivated land in mountainous areas will reduce soil disturbance and have a positive effect on soil erosion control; even in an environment prone to soil erosion, the content of water-stable aggregates and the conversion rate of soil carbon will increase gradually over time. (Dai et al., 2007; Dai et al., 2008; Renwick et al., 2013). Studies on carbon fixation have shown that the carbon fixation rate is closely related to the tree age structure, and the fixation rate of young and middle-age forest is relatively high, whereas that of mature and over-mature forest declines gradually; in this sense, the compensated forest land has a stronger effect on carbon fixation (Xu et al., 2010). Consequently, as long as the ecological restoration management measures are adapted and a certain period of time is allowed, compensated forest land could provide the same ecological regulation services as occupied one.

6 Conclusion

Taking Wannian County, a typical mountainous agricultural area in China, as an example, this study explored the impact of the CLRB system and the LID policy on the use of cultivated land in mountainous counties from a micro-perspective. The results show that from 2010 to 2020, CCL reclaimed from rural settlements has shifted uphill, with considerable fragmentation and an abandonment rate of 14.77%. The new abandonment is not related to agricultural suitability such as cultivated land quality, slope and aspect, but rather to its altitude, distance to adjacent cultivated land and patch area. This isn't the same as the abandonment of cultivated land reclaimed spontaneously from natural ecosystems by humans. Finally, this resulted in a 297.48 t loss of grain production capacity throughout the county. Based on the results of driving force analysis, a solution from NRRB that restructure the spatial layout arrangement of cultivated land, forest land and construction land, was put forward under the coupling framework of land use "Condition-Status-Function." The CAFL could be identified though the establishment of a new evaluation system for cultivated land reserve resources. The quality of the cultivated land obtained from the reclamation of CAFL would be better than that of abandoned CCL. By reclaiming the spare forest land from a portion of the CALF, it is sufficient to compensate for the loss of grain production capacity from the abandoned CCL, and reduces the risk of new abandonment. While this solution would also result in a certain loss of ecological regulation services in the short term. However, in most southern mountainous areas of China, the forest cover would be restored quickly with suitable ecological restoration management measures, and provides an ecological regulation service equivalent to that of reclaimed CAFL.

Data availability statement

The datasets presented in this article are not readily available because the datasets including the spatial data of LID in the study area sourced from the non-public information of the local government. Requests to access the datasets should be directed to the corresponding author, Li Chao (lichaonongda@163.com).

Author contributions

Conceptualization, ZX; data curation, ZX, and YZ; formal analysis, ZX, and YZ; funding acquisition, ZX; investigation, SF, and CL; methodology, ZX and YZ; project administration, SF and SD; resources, SF and SD; software, ZX, YZ, and SD; supervision, CL and SD; validation, ZX, YZ, and SD; visualization, YZ and SD; writing—original draft, ZX and SD; writing—review and editing ZX and SD.

Funding

The authors gratefully acknowledge the financial support by the National Natural Science Foundation of China (42201280) and the Major Project Funding for Social Science Research base in Fujian Province Social Science Planning (FJ2021MJDZ019).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 05 April 2023
DOI 10.3389/fenvs.2023.1078565

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OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Land Use Dynamics, a section of the journal Frontiers in Environmental Science

RECEIVED 24 October 2022
ACCEPTED 20 February 2023
PUBLISHED 05 April 2023

CITATION
Liu M, Qi D and Zhong T (2023), Agricultural development policy diffusion associated with leading cadre's experience and expansion of protected agriculture in China.
Front. Environ. Sci. 11:1078565.
doi: 10.3389/fenvs.2023.1078565

Agricultural development policy diffusion associated with leading cadre's experience and expansion of protected agriculture in China

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Protected agriculture has notably expanded since 2010 in China and many factors have influenced protected agricultural expansion. Yet little attention has been paid to how the successful experiences of protected agriculture demonstration areas have been diffused. Leading cadres are considered to play an important role in the policy diffusion process, yet little attention has been paid to the influence of leading cadres with connections to industry demonstration regions on industry development. Thus, this study examined the impact of mayors and municipal party secretaries connected to four protected agriculture demonstration regions—Shandong Province, Jiangsu Province, Hebei Province, and Liaoning Province—on the expansion of protected agriculture. This study used panel data from 314 prefectural-level cities and 1792 counties for the period 2014–2018 and the multidimensional fixed-effects model for a quantitative study. The results show that connected mayors significantly contribute to the expansion of protected agriculture, with the scale of protected agriculture in the county-level areas under their jurisdiction being on average 10.8% higher than that in areas under the jurisdiction of unconnected mayors. The effect of connected municipal secretaries on the expansion of protected agriculture was not significant. In addition, there were geographical differences in the impact of leading cadres on the expansion of protected agriculture. The positive impact of leading cadres on the protected agriculture expansion is significantly weakened when the area under their jurisdiction is located in the less economically developed western region or is part of the comprehensive climate unsuitable area during the March-June sowing period. The leading cadres connected to Shandong Province, Liaoning Province, and Jiangsu Province respectively had significantly different but positive impacts on the expansion of protected agriculture.

KEYWORDS

protected agriculture expansion, favoritism in leading cadres' decisions, the propensity score matching model, the difference in differences model, China

1 Introduction

Protected agriculture (PA, *SheShiNongYe* in Chinese) refers to a series of agricultural technologies that can increase crop yield, specifically including mulching, high tunnel, greenhouse, controlled environment agriculture, and drip irrigation (Jensen and Malter, 1995; Takeshima and Joshi, 2019). In the process of agricultural transition to sustainable intensification, PA has gained increasing attention as an industrialized agricultural

10.3389/fenvs.2023.1078565

production method that uses technological engineering tools to control the production environment (Xie et al., 2017). PA has made an important contribution to meeting people's food needs, improving resource utilization efficiency, and promoting farmers' income growth. From 1980 to 2010, the area of PA worldwide has multiplied several times (Takeshima and Joshi, 2019). In China, PA has expanded rapidly since the mid-1990 s. In 2009, the total scale of PA in China was already the largest in the world, and by 2019 it covered 4.1 million hectares, with an annual output value of 980 billion yuan, more than 1/3 of the total agricultural output (Li, 2021); while the current annual output of greenhouse vegetables is 265 million tons, accounting for 1/3 of the total output (Li, 2022). Understanding the trends and driving mechanisms behind the expansion of PA in different regions is an important guide to accelerate the sustainable development of PA and provide a rational orientation for the transformation of agricultural and rural modernization (Wu and Zhang, 2013).

Existing studies have focused more on the development status of PA and have examined multiple factors that influence the expansion of PA, of which policy factors have been widely recognized as one of the most important contextual factors (Zhong et al., 2020). For example, Iceland's tariff policy and electricity subsidy policy have contributed to the continued development of greenhouse agriculture (Butrico and Kaplan, 2018). Chinese government-led food localization programs, aimed at stabilizing the local food supply, had also led to the expansion of greenhouse agriculture (Zhong et al., 2020). In fact, PA is a high-input, technology- and labor-intensive industry that needs to be incentivized by supportive government policies or plans for land use and industrial restructuring (Takeshima and Joshi, 2019). Therefore, the expansion of PA in different regions is not only the independent choice of farmers, but the influence of the diffusion of relevant policies or policy innovations among different governments may be more important (Lybbert and Sumner, 2012). However, few studies have analyzed agricultural development policy diffusion associated with the leading cadre's experience and expansion of PA. Unlike other countries and regions around the world, local officials in China's local political system have strong executive decision-making power (Chen Z. et al., 2019) and are important actors in driving policy diffusion (Liu and Yi, 2021). Research on policy diffusion has focused more on exploring diffusion mechanisms (Shipan and Volden, 2008), and some studies have focused on the facilitation effects generated by leading cadres and leadership transfer networks (Liu and Yi, 2021). However, little attention has been paid to the impact of the experience accumulated by leading cadres in specific regions with prominent industrial development on the diffusion of relevant industrial policy innovations, such as those in regions with prominent PA industry. It has been shown that leading cadres will disseminate and develop professional experience, institutional knowledge, and innovative ideas accumulated continuously in the workplace along their career paths, especially in the development of prominent industries in their birthplace and in the regions where they had served (Liu and Yi, 2021).

This study attempts to examine whether and how the expansion of PA is associated with leading cadres' experiences such as birth place and working place, which could influence agricultural development policy diffusion. According to the 2006 and 2016 agricultural census reports, four regions in China—Shandong Province, Jiangsu Province, Hebei Province, and Liaoning Province—have far surpassed other regions in China in terms of the scale and expansion rate of PA since 2006 (State Statistics Bureau, 2017). These four regions have developed mature models of PA development and play an important role as demonstration leaders in promoting PA expansion and technological innovation. Thus, the influence of policy diffusion on leading cadres' behavior in these four regions cannot be ignored when exploring the driving mechanism of China's PA expansion. To address this gap, this paper applies a multidimensional fixed-effects model to quantitatively analyze data on municipal leading cadres and the scale of PA from 2014 to 2018. This paper attempts to examine the role of leading cadres in the diffusion of PA, particularly to analyze the possible impact of the experience accumulated by leading cadres in Shandong, Jiangsu, Hebei, and Liaoning provinces on the expansion of PA and its differences. This paper offers a new perspective to promote the development of agricultural modernization in China and other countries undergoing rapid transition by exploring the mechanisms of diffusion of experience in the expansion of PA.

The next section theoretically constructs an analytical framework to explore the correlation between the expansion of PA and favoritism in leading cadres' decisions among policy diffusion and to formulate the hypotheses. Section 3 and Section 4 respectively introduce the data and methodology, and the empirical results of testing each hypothesis. Section 5 provides relevant discussions of each hypothesis. Finally, conclusions, policy implications, and research agendas are summarized in Section 6.

2 Theoretical framework

Policy diffusion refers to the spread of policy programs, development models, relevant knowledge, information, or experiences from one sector or region to another (Danaeefard and Mahdizadeh, 2022). Among them, policy actors or change agents play an important role in the process of policy diffusion (Liu and Yi, 2021). Research on policy diffusion suggests that the specific networks in which leading cadres are embedded influence the mechanisms, scope, and effects of policy diffusion (Shipan and Volden, 2012). Over the entire career of a leading cadre, his or her working experience is continuously enriched and gradually internalized into leadership competencies, while the social network of the leading cadre expands as he or she shifts from one place to another (Yi et al., 2018). The informal connection network between leading cadres and their birthplace and served/serve place can lead to governing preference, which in turn affects the governing strategies of leading cadres (Chen Z. et al., 2019; Mansha et al., 2022). Considering that PA is different from traditional agriculture, the former is an industry that requires local governments to make arable land resource utilization and agricultural production plans in advance, and invest more extra costs in terms of equipment, technology, and labor (LaPlante et al., 2021). And connected leading cadres with practical experience in PA would prioritize the application or innovation of relevant knowledge in their jurisdictions. Thus, connected leading cadres can help facilitate the expansion of PA. Compared with other regions in China, four regions—Shandong Province, Jiangsu Province, Hebei Province, and Liaoning Province—have an early start, faster development, and larger scale of PA. These four regions have developed diverse PA production technologies, management models, and well-developed supply chains for greenhouse vegetables, which are significant concentrations of China's PA industry (State Statistics Bureau, 2017). Also, the mature experiences of these four regions in terms of production technologies and business management models of PA are important references for the widespread expansion of PA and the transformation of agricultural modernization (Bai and Zhang, 2021). Based on this, we propose hypothesis 1 (H1): municipal leading cadres (mayors, municipal party secretaries) who grew up or served/serve in Shandong, Jiangsu, Hebei, and Liaoning provinces are likely to have accumulated more knowledge and practical experience regarding the expansion of PA and would show favoritism in decisions of promoting PA expansion.

The governing decisions of leading cadres are complex and are constrained by a variety of factors such as the initial socioeconomic and resource endowment conditions, the development goals, and the personal experience and ability of the leading cadres (Wang et al., 2016; Wen et al., 2017; Chen Z. et al., 2019; Wang, 2022). On the one hand, considering the differences in development conditions between different served/serve places, rational leading cadres would not blindly copy the successful experiences of other regions, but would selectively apply their acquired experiences or would make adaptive innovations when promoting a certain development model (Liu and Yi, 2021). On the other hand, although the four regions we mentioned, Shandong, Jiangsu, Hebei, and Liaoning provinces, are all prominent in China in the field of PA, they are not exactly the same in terms of specific production models and business models, etc. This means that there would be differences in the diffusion effects of different types of PA development models, e.g., certain models are more adaptable in other regions, making it less difficult and risky for leading cadres to diffuse corresponding policies in these regions. That is, leading cadres connected to different prominent regions of PA acquire different industrial development experiences and social networks, and in turn, they show different governing preferences in the present serve regions. Based on this, we put forward hypothesis 2 (H_2): different regions are differentially influenced by the governing preferences of connected leading cadres in terms of PA expansion, and the leading cadres with connections to Shandong, Jiangsu, Hebei, and Liaoning provinces respectively will have different impacts on the decisions regarding the promotion of PA.

3 Methods and data

3.1 Methodology and model specification

The main purpose of this study is to examine the causal relationship between the decisions of leading cadres with governing preference and the expansion of PA. That is, this study requires a valid measure on governing preferences that may continuously arise during the career transfer process of leading cadres, which is a challenge. This is because the promotion or transfer of leading cadres is not random in China's political system, and the measurement of governing preferences of leading cadres needs to address endogenous formation (Zhang and Yang, 2022). Moreover, it is difficult to directly observe the experience gained by leading cadres in these regions. Leading cadres who have worked longer periods of time may have accumulated more managerial experience and have a greater willingness to adopt a high-input, high-risk, high-output development model (Chen S. et al., 2019). Therefore, the estimation results may incorrectly attribute unobserved capacity differences to the explanation of the impact of leading cadres with governing preference on PA expansion. To measure the causal relationship between leading cadres with governing preference and the expansion of PA, this study considers leading cadres who grew up or served/serve in Shandong, Jiangsu, Hebei, or Liaoning provinces as having governing preferences. And this study constructs a multidimensional fixed effects model that includes the fixed effects of leading cadres characteristics, regions, and years (Xu, 2018). The baseline model is as follows (see Eq. 1):

$$PA_{it} = \beta_0 + \beta_1 Treat_{it} + \beta_2 Time_{it} + \beta_3 Treat_{it} \cdot Time_{it} + \delta \sum\nolimits_n X_{it} + A_i + B_t + C_p + \varepsilon_{it} \tag{1}$$

Where i represents the region (county-level), p represents the city, t stands for the year, PA_{it} denotes the PA area in year t of county i. $Treated_{it}$, as a treatment variable, denotes "whether there is a leading cadre with governing preference in region i during the study period", and if yes, the sample is the treatment group and $Treated_{it}$ is 1. If otherwise, the sample is the control group, the $Treated_{it}$ is 0. $Time_{it}$, as a time dummy variable, indicates "whether the city p is served by a leading cadre with governing preferences in year t", and if yes, $Time_{it}$ is 1; if otherwise, $Time_{it}$ is 0. $Treat_{it} \cdot Time_{it}$ is the core explanatory variable that indicates the effect of leading cadres with governing preferences on the expansion of PA, and this estimated coefficient needs to be focused. If the value is significantly positive, it indicates that leading cadres with governing preferences promote the expansion of PA. β_0 is a constant term and X_{it} is a set of covariates. A_i indicates the individual fixed effect of county i , which absorbs the heterogeneity associated with the experience accumulated locally by leading cadres. C_p is the regional fixed effect of city p, which is used to absorb the unobserved regional resource endowment. B_t is a time fixed effect to absorb unobserved time shocks and ε_{it} denotes the random perturbation term.

3.2 Dependent and independent variables

Referring to the existing literature, this paper sets the current year's PA land area as the explanatory variable to characterize the development of PA instead of the annual change in land use. Since the PA development level varies from place to place and the scale varies widely, to eliminate possible heteroscedasticity, the area data take a logarithmic form.

This study focuses on the influence of leading cadres with governing preference on the expansion of PA. Studies have shown that provincial leading cadres' decisions are more

TABLE 1 Variables description and summary statistics.

Set	Variable (*variable symbol*)	Definition (unit)	Mean	Max	Min
Outcome	Scale of protected agriculture (*lnPA*)	The log value of the scale of the protected agricultural area (ha)	5.778	14.655	0
Treatment	Treat	Whether the cadre (mayor or municipal party secretary) has grown up or has worked in Shandong, Jiangsu, Hebei, and Liaoning provinces, *Treat* = 1 if Yes; otherwise, *Treat* = 0	0.378, 0.415	1, 1	0, 0
PC	Age (*Age*)	Age of the cadre (ages)	51.974, 53.897	62, 61	38, 43
	Age over 55 (*Age55*)	Whether the cadre aged 55 or over, *Age55* = 1 if Yes; otherwise, *Age 55* = 0	0.235, 0.437	1, 1	0, 0
	Tenure (*Tenure*)	Length of local service of the cadre (years)	2.564, 2.528	11, 9	1, 1
SEC	Municipal GRP (*lnMpgrp*)	The log value of municipal gross regional product *per capita* (10,000 yuan/person)	1.199	3.324	−0.308
	Municipal agricultural output (*Mprimary*)	The ratio of the added value of the municipal primary industry to municipal gross regional product (%)	0.168	0.571	0.014
	County industrial development (*Rsgrp*)	The ratio of the added value of county secondary industry to gross regional product (%)	0.424	0.887	0.013
	Municipal financial pressure (*lnMfpressure*)	The log value of municipal public finance gap (10,000 yuan)	13.872	15.584	−14.35
	County financial pressure 1 (*Rfpressure*)	The ratio of the county public finance gap to gross regional product (%)	0.230	3.781	−0.469
	County financial pressure 2 (*lagFpressure*)	One-period lag value of county public finance gap (10,000 yuan)	174,644	1,202,550	−66471
	Municipal population pressure (*lnMpopulation*)	The log value of municipal population density (people/square kilometers)	5.132	7.776	−0.354
NC	Climate unsuitable area72 (*Unsuit72*)	Whether it is a climate-unsuitable area for conducting protected agriculture from July to February, *Unsuit72* = 1 if Yes; otherwise, *Unsuit72* = 0	0.566	1	0
	Climate unsuitable area36 (*Unsuit36*)	Whether it is a climate-unsuitable area for conducting protected agriculture from March to June, *Unsuit36* = 1 if Yes; otherwise, *Unsuit36* = 0	0.752	1	0

influenced by central government power, while county-level leading cadres are mostly local and rarely experience workplace changes across provinces or municipalities (Yao and Zhang, 2015; Chen S. et al., 2019). Therefore, it is more reasonable to explore the governing preferences of municipal-level leading cadres. Moreover, in China's political system, there are some differences in the responsibilities of mayors and municipal party secretaries. Therefore, this study used the dummy variables *MTreat* and *STreat* to characterize whether the mayor and the municipal party secretaries have governing preferences, respectively, as the core explanatory variables of the model. In addition, the suffixes *s*, *j*, *h*, and *l* were added after the above variable names to distinguish whether the preferences of leading cadres for PA expansion are associated with the experiences gained in Shandong, Jiangsu, Hebei, and Liaoning provinces, respectively.

Since the expansion of PA is also influenced by other factors, three sets of covariates were included in the model with reference to the existing literature to reduce estimation bias caused by omitted variables. As shown in Table 1, one group is *PC* (representing the leading cadres' personal characteristics), one group is *SEC* (representing the socio-economic development characteristics), and the last group is *NC* (representing the regions' natural characteristics).

The personal characteristics of the leading cadres affect the extent to which the government implements different policies (Chen et al., 2017; Chen Z. et al., 2019; Meng et al., 2019). For example, the age and the length of locality tenure of the leading cadres are correlated with their perceptions of career promotion prospects and their identity to served place. Scholars mostly believe that the younger the leading cadres are and the shorter their tenure in the local area, the more they tend to adopt behaviors that will lead to substantial regional economic development in the short term and achieve their promotion goals (Chen et al., 2017). As the age increase, there will be a turning point in the promotion probability of leading cadres. And it has been demonstrated that leading cadres would choose a more conservative governing strategy after that turning point at around 54 years old (Chen S. et al., 2019). Thus, this study used the continuous variables *Tenure* and *Age*, as well as the dummy variable *Age55* (indicating the leading cadre aged 55 or over) to characterize the personal characteristics of the leading cadres. In addition, the prefixes *M* and *S* were added in front of the above variables' names to distinguish the characteristics of mayors and municipal party secretaries.

The socioeconomic development status of the region is characterized by economic indicators, industrial development indicators, financial pressure indicators, and demographic indicators. Firstly, there is a positive relationship between economic development and agricultural development, and most regions with rapid economic development also experience greater growth in agriculture (Valdés and Foster, 2010). Thus, this study used a continuous variable *lnMpgrp* (representing the log value of municipal gross regional product *per capita*) to reflect the level of regional economic development (Zhang and Lu, 2016). Secondly, the impact of regional industrialization on agricultural development is bilateral. If a city experiences industrialization at the expense of agricultural degradation, landscape fragmentation in that region would inhibit PA expansion (Fan, 2004). If a region adopts a new industrialization technology that coordinates the development of industry and agriculture, it may bring new opportunities for PA expansion (Fan, 2004). An increase in agricultural output effect indicates the improvement of the degree of agricultural modernization and the enhancement of the possibility of PA expansion (Huang, 2010). Therefore, this study includes the continuous variable *Mprimary* (representing the ratio of the added value of the municipal primary industry to gross regional product) to capture the agricultural output effect and the continuous variable *Rsgrp* (representing the ratio of the added value of county secondary industry to gross regional product) to characterize the industrialization of the region. Finally, it has been suggested that the regional fiscal pressure will have an impact on land finance decisions in the following year, while there may be some inertia effects on the scale and structure of financial expenditures (Wu et al., 2019), which will, in turn, affect the PA expansion. Therefore, this study used the continuous variables *lnMfpressure* (representing the log value of municipal public finance gap), *Rfpressure* (representing the ratio of the county public finance gap to gross regional product), and *lagFpressure* (representing the one-period lag value of county public finance gap) to measure the perceived financial pressure of local governments (Wang et al., 2013; Yang and Peng, 2015; Wang and Yin, 2019; Wu et al., 2019). Under fast urbanization, a substantially growing urban population has raised the demand for urban construction land, which in turn has increased the difficulty of expanding PA (Liu et al., 2020). Therefore, this study used the continuous variable *lnMpopulation* (representing the log value of municipal population density) to characterize the demographic pressure on regional development.

The natural characteristic of the region is characterized by regional climatic suitability. Although PA has the advantage of year-round production compared to open-air agriculture, uncertain weather conditions would still affect the construction cost of PA facilities and the management cost in the production process (Eben-Chaime et al., 2011). Due to the vast size of China, the climatic characteristics and the types of natural disasters that may be encountered vary from place to place, resulting in different climatic suitability for the development of PA in different regions (Gao et al., 2022). Zhang et al. (2021) evaluated the climatic suitability of PA based on day-by-day meteorological data from 1990 to 2019 in China. The results showed that during the sowing period from July to February each year, the unsuitable areas were mainly clustered in northeast, northwest, southwest, and north China; during the sowing period from March to June each year, the unsuitable areas were mainly clustered in south-central, north-western, and south-western regions of China (Zhang et al., 2021). In this study, the dummy variables *Unsuit72* and *Unsuit36* were set to characterize the areas that were part of the combined climate unsuitable zone in the two sowing periods, respectively.

3.3 Data sources

This paper uses panel data on the characteristics of municipal-level cadres matched with county-level macro statistics from 2014 to 2018 for quantitative estimation in 314 prefecture-level cities and 1,792 counties in China. On the one hand, personal and tenure information of municipal-level leading cadres is obtained from public platforms such as People's Daily Online, Xinhua Online, and Baidu Search, and is manually compiled by the authors. On the other hand, regional macroeconomic data is collected from the China County Statistical Yearbook (County and City Volume) from 2015 to 2019 (National Bureau of Statistics Rural Socio-Economic National Bureau of Statistics Rural Socio-Economic Survey, 2015, 2019). Considering the special administrative divisions of the four Chinese municipalities (Beijing, Tianjin, Shanghai, and Chongqing), and the missing data of key variables in Hong Kong, Macao, Taiwan, and some other counties and cities, the data of these areas are excluded. The moving average method is used to deal with some missing values.

4 Empirical results

The empirical results of this paper comprise mainly consist of three aspects: the first is to test H1 by examining whether the governing preferences for promoting the PA expansion are associated with the municipal leading cadres with connections to Shandong, Jiangsu, Hebei, and Liaoning provinces. The second is to test H_2 by analyzing whether there are regional differences among the governing preferences of leading cadres and comparing whether there are differences in the governing preferences of leading cadres connected with different regions. And the last is about model robustness tests.

4.1 Estimation results of protected agriculture expansion decisions

Based on the above model settings, the results are shown in Table 2. The coefficient for the core explanatory variable in Model (1) is positive and statistically significant at 1% level. Model (2), which adds covariates into the model, also shows a positive coefficient significant at 1% level. Models (3)–(5) take individual, regional, and time-fixed effects into account, respectively, among which the coefficients of the core explanatory variable regression are similar and remain statistically significant. The model fitting effect gets significantly improved as the increasing value of fitting efficiency (R2), and the decreasing results of Akaike

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TABLE 2 Estimation results of leading cadre's favoritism on protected agriculture expansion decisions.

Variable	Model (1)	Model (2)	Model (3)	Model (4)	Model (5)	Model (6)
MTreat·Time	**0.443*** (0.066)**	**0.185*** (0.064)**	**0.541*** (0.048)**	0.023 (0.069)	**0.108* (0.069)**	**0.114* (0.069)**
MAge		**0.016** (0.007)**	**0.045*** (0.008)**	**0.012** (0.006)**	**0.011* (0.006)**	**0.012** (0.006)**
MAge55		−0.063 (0.044)	**−0.177*** (0.062)**	−0.064 (0.042)	−0.004 (0.042)	−0.008 (0.042)
Unsuit72		0.000 (0.099)	0.083 (0.052)			
Unsuit36		−0.114 (0.104)	0.062 (0.056)			
Mprimary		**3.292*** (0.585)**	**3.547*** (0.340)**	**1.956** (0.823)**	**2.724*** (0.833)**	**2.707*** (0.851)**
lnMpopulation		**0.583*** (0.033)**	**0.584*** (0.018)**	−0.172 (0.259)	−0.066 (0.257)	−0.116 (0.258)
lnMpgrp		**0.685*** (0.085)**	**0.893*** (0.048)**	0.159 (0.123)	**0.979*** (0.150)**	**0.906*** (0.160)**
lnMfpressure		−0.006 (0.012)	**−0.016* (0.009)**	0.007 (0.009)	0.011 (0.009)	0.012 (0.009)
Rsgrp						0.179 (0.331)
cMTreat·Time_cRsgrp						**0.951***(0.358)**
Constant	**5.638*** (0.046)**	0.710 (0.469)	**−1.249*** (0.442)**	**5.411*** (1.357)**	**3.727*** (1.363)**	**3.925*** (1.365)**
Individual effect	No	No	Yes	Yes	Yes	Yes
Regional effect	No	No	No	Yes	Yes	Yes
Time effect	No	No	No	No	Yes	Yes
R^2_a			0.206	0.763	0.766	0.767
AIC			36,130.033	23,311.063	23,168.213	23,163.036
BIC			36,201.024	23,367.855	23,225.006	23,234.026

Notes: *, **, and*** represent statistically significant at the level of 10%, 5%, and 1%, respectively, the same as below. The meaning of bold font that we want to highlight the significant results of the estimation.

information criterion (AIC) and Schwartz or Bayesian information criterion (BIC) are shown. According to Model (5), connected mayors could significantly increase the scale of PA by 10.8%, which confirms hypothesis 1. In Model (6), the coefficient of the interaction term is statistically significant and positive with 0.951, which indicates that the better-developed secondary industry in county-level areas could significantly enhance the governing preference of connected mayors for PA expansion. Among the results of Model (1)-Model (6), the coefficients of the core explanatory variable and relevant covariates largely maintain consistency in sign, direction, and significance, which means mayors with connections to Shandong, Jiangsu, Hebei, or Liaoning provinces have a significant contribution to PA expansion. Besides, the results of connected municipal party secretaries were not reported due to their insignificant effect on PA expansion.

4.2 Estimation results for the impact of regional differences in governance favoritism

Based on Model (5) above, regional variability among the effects of leading cadres' governing preferences on PA expansion is estimated by adding interaction terms between leading cadres and regional dummy variables and also by replacing the core explanatory variables for leading cadres connected with Shandong, Jiangsu, Hebei, and Liaoning regions, respectively.

The results of Model (7)-Model (9) in Table 3 indicate that the positive impact on PA expansion would be significantly weakened among connected leading cadres who are serving in the western region or the comprehensive climate unsuitable regions. Specifically, the coefficients of the interaction term in Model (7) and Model (8) are both statistically significant and negative, with −0.268 and −0.279. While that of leading cadres' governing preference variables are both statistically significant and positive, with 0.218 and 0.204. This indicates that the positive influence of connected leading cadres on the expansion of PA would be decreased by regional characteristics when the jurisdiction is located in the western region. Similarly, the coefficient of the interaction term in Model (9) is statistically significant and negative, with −0.226. Thus, the positive effect on PA expansion of connected leading cadres who are in areas that are part of comprehensive climatic unsuitable areas during the March-June sowing period would be greatly influenced by climatic characteristics, such as high temperatures and lack of sunlight (Zhang et al., 2021). Besides, the coefficients of the leading cadres' governing preference in Model (10)-Model (12) are significantly positive but different. Mayors with connections to Jiangsu, and municipal party secretaries with connections to Shandong and Liaoning provinces all have significant positive governing preferences for expanding the scale of PA by 0.293, 0.150, and 0.408, respectively. That is, the influence of different regions on

TABLE 3 Estimation results of regional difference on leading cadre's favoritism.

Variable	Model (7)	Model (8)	Model (9)	Model (10)	Model (11)	Model (12)
MTreat·Time	**0.218** (0.088)**					
MSTreat·Time		**0.204** (0.099)**	**0.187* (0.108)**			
MTreat·Time_j				**0.293** (0.122)**		
STreat·Time_s					**0.150** (0.061)**	
STreat·Time_l						**0.408*** (0.154)**
MAge	**0.011* (0.006)**			0.009 (0.006)		
MAge55	−0.007 (0.042)			−0.001 (0.042)		
Age		0.014 (0.009)	0.015 (0.009)			
Age55		**−0.079* (0.041)**	**−0.083** (0.041)**			
SAge					−0.013 (0.008)	−0.011 (0.008)
SAge55					0.045 (0.042)	0.047 (0.042)
Mprimary	**2.842*** (0.835)**	**2.875*** (0.831)**	**2.835*** (0.831)**	**2.674*** (0.833)**	**2.657*** (0.829)**	**2.546*** (0.829)**
lnMpopulation	−0.054 (0.257)	−0.015 (0.258)	−0.010 (0.258)	−0.055 (0.257)	−0.082 (0.257)	−0.035 (0.257)
lnMpgrp	**0.978*** (0.150)**	**1.013*** (0.150)**	**1.047*** (0.150)**	**0.953*** (0.150)**	**1.007*** (0.148)**	**0.994*** (0.148)**
lnMfpressure	0.011 (0.009)	**0.015*(0.009)**	**0.015*(0.009)**	0.011 (0.009)	0.014 (0.009)	0.015*(0.009)
MTreat·Time_Warea	**−0.268** (0.135)**					
MSTreat·Time_Warea		**−0.279** (0.125)**				
MSTreat·Time_Unsuit36			**−0.226* (0.130)**			
Constant	**3.652*** (1.363)**	**3.190** (1.447)**	**3.090** (1.451)**	**3.813*** (1.363)**	**4.996*** (1.418)**	**4.680*** (1.419)**
Individual effect	Yes	Yes	Yes	Yes	Yes	Yes
Regional effect	Yes	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes	Yes
R^2_a	0.767	0.766	0.766	0.767	0.766	0.766
AIC	23,165.282	23,223.467	23,225.929	23,164.082	23,222.249	23,221.002
BIC	23,229.173	23,287.372	23,289.833	23,220.874	23,279.053	23,277.807

The meaning of bold font that we want to highlight the significant results of the estimation.

the leading cadres with whom they are connected varies, and the successful experience of PA in Liaoning Province may be relatively easier to spread.

4.3 Model robustness test

(1) Changes in estimation method. Considering that the non-random promotion or transfer of leading cadres may cause bias in sample selection and estimation results. Therefore, this part first adopts the PSM method to remove the mismatched samples and then re-estimates the multidimensional fixed-effects model of Model (5). Among them, the PSM method is applied with the kernel matching method, and the covariates of the model include the regional socioeconomic development characteristics and natural characteristics mentioned above. The estimation results of the core explanatory variables and relevant control variables of Model (13) in Table 4 are generally consistent with those of Model (5) in Table 2. This indicates that the results estimated using the multidimensional fixed effects model in the main text are robust and less affected by sample selection bias.

(2) Substitution of independent variables. In this section, the variable *lnPA* is replaced by the original value (*PA*), annual variation (*dPA*), the one-period lag value of PA (*lagPA*), and the log value of the one-period lag value of PA (*lnlagPA*) respectively. The fitting effects of Model (14)-Model (16) in Table 4 are very poor, while the estimation of Model (17) is closer to that of Model (5) in Table 2. This means that the logarithmic treatment for the scale of PA in the main text well reduced the effect of abnormal values. Also, the effect of favoritism in mayors' decisions on PA expansion is rarely affected by the scale of PA in the previous year.

TABLE 4 Estimation results of the robustness test.

Variable	Model (13)	Model (14)	Model (15)	Model (16)	Model (17)
	Y = lnPA	Y=PA	Y = dPA	Y = lagPA	Y = lnlagPA
MTreat·Time	**0.141** (0.070)**	858.872 (1759.831)	831.801 (2,709.682)	27.399 (1713.305)	−0.009 (0.047)
MAge	0.006 (0.006)	23.197 (153.698)	60.051 (236.795)	−39.454 (149.723)	0.006 (0.004)
MAge55	0.013 (0.044)	−57.189 (1,079.347)	−455.821 (1,666.698)	426.056 (1,053.836)	−0.028 (0.029)
Mprimary	**3.797*** (0.892)**	−13740.432 (21,391.828)	−14663.871 (32,840.600)	1856.002 (20,764.785)	**1.934*** (0.566)**
lnMpopulation	−0.074 (0.270)	1986.196 (6,550.040)	42.160 (10,145.080)	1805.732 (6,414.633)	0.110 (0.175)
lnMpgrp	**1.080*** (0.159)**	−1,695.057 (3,827.520)	−2,763.585 (5,897.727)	1,168.681 (3,729.074)	**0.514*** (0.102)**
lnMfpressure	0.015 (0.010)	−64.430 (221.946)	−89.979 (338.478)	32.366 (214.016)	0.010 (0.006)
Constant	**3.801** (1.499)**	−4,516.557 (34,750.333)	3,534.380 (53,731.478)	−7,589.496 (33,973.878)	**3.860*** (0.926)**
Individual effect	Yes	Yes	Yes	Yes	Yes
Regional effect	Yes	Yes	Yes	Yes	Yes
Time effect	Yes	Yes	Yes	Yes	Yes
R2_a	0.745	0.010	−0.251	0.015	0.885
AIC	21,381.098	201,631.209	212,530.237	204,327.501	16,267.119
BIC	21,437.227	201,687.889	212,587.030	204,384.294	16,323.911

The meaning of bold font that we want to highlight the significant results of the estimation.

5 Discussions

5.1 Positive effect of leading cadre's favoritism on protected agriculture expansion

Municipal leading cadres with connections to Shandong, Jiangsu, Hebei, or Liaoning provinces have certain favoritism in decisions for developing PA. The scale of PA in county-level areas under the jurisdiction of connected mayors is on average 10.8% higher than that of those under mayors without connections, and the statistically significant of this estimation is at 10% level. The age of the mayor also has a significant positive effect on PA expansion. As the mayor's age increases by 1 year, the scale of PA will significantly increase by 1.1%. However, unlike connected mayors, the estimates of the effect of connected municipal party secretaries on PA expansion are not statistically significant. This may be due to the difference in the responsibilities between mayors and municipal party secretaries.

According to the theory of agent network division, the career transfer of leading cadres is accompanied by the cross-regional or inter-organizational diffusion of policy innovations (Yi et al., 2018). When leading cadres transfer from jurisdiction i to jurisdiction j, they will bring their professional experience, management knowledge, and innovative policy ideas accumulated in previous served places to their new workplaces (Liu and Yi, 2021). The older the leading cadres are, the more experience they accumulate, which contributes to policy diffusion. For example, in 2012, an official who was born in Hebei Province and had served in Hebei Province was transferred to Guangyuan City, Sichuan Province, and in 2016 the official was appointed as the mayor of Guangyuan City. From the relevant statistics, it can be seen that the average expansion rate of PA in the city in 2016–2018 has greatly increased compared to that in 2014–2015, from an average growth of 86 ha per year to 163 ha per year (National Bureau of Statistics Rural Socio-Economic Survey, 2015, 2019). Referring to relevant news reports after the official took office, we find that the mayor made a clear commitment to focus on developing modern agriculture in the meeting in which he was officially appointed, and paid particular attention to agricultural modernization and transformation during his subsequent tenure (Guangyuan Agricultural Bureau, 2016; Guangyuan Daily, 2016). He not only visited rural areas several times to investigate the current state of the agricultural industry but also initiated projects for several modern agricultural parks construction and upgrading of existing parks (Sichuan Daily, 2016; Guangyuan Municipal Government Office, 2018). Taken together, the official's positive influence on the agricultural industry transformation and PA expansion likely stems from his professional experience accumulated in his birthplace and former place of employment (Hebei Province), as well as his approximately 4-year tenure in Guangyuan City. These experiences not only gave him a deeper understanding of the modern agricultural development model in Hebei Province but also enabled him to make well-targeted agricultural transformation proposals based on the local resources and industrial characteristics of Guangyuan City, which in turn led to the effective diffusion of the PA model in Guangyuan City.

Connected mayors and municipal party secretaries are not consistent in their influence on policy diffusion among leadership agent networks. In China's local political system, local officials include the mayor and the municipal party secretary (Chen Z. et al., 2019). They have different responsibilities. The former is in

10.3389/fenvs.2023.1078565

charge of administration, while the latter manages party affairs (Lu and Wang, 2019). Although municipal party secretaries are more powerful than mayors, the mayor has more specific responsibility than the municipal party secretary on decisions regarding economic development and social management (Lu and Wang, 2019). That is, connected mayors have a more prominent positive influence in deciding whether to promote the expansion of PA and in specifying specific plans for PA development, supporting facilities construction, and project initiation. Whereas, connected municipal party secretaries are likely to focus more on adopting practices that will result in rapid and significant regional economic uplift.

5.2 Geographical differences among leading cadre's favoritism and protected agriculture expansion

There are significant geographical differences in the positive impact of connected leading cadres on policy diffusion. For those jurisdictions in western China, the positive effects of connected mayors and municipal party secretaries on PA expansion were significantly weakened and statistically significant were both at 1% level. Also, the positive effect of connected municipal party secretaries on PA expansion was significantly weakened at 10% level, for those jurisdictions that were part of the comprehensive climate unsuitable areas during the March-June sowing period. This may be related to regional characteristics. In addition, there are differences in the positive impact of policy diffusion among leading cadres with connections to different regions. The positive impact of mayors connected with Liaoning province is relatively the highest, followed by municipal party secretaries connected with Jiangsu province, and the relatively lowest is the mayors connected with Shandong province. This may be due to the popular models of PA in these four regions are different and thus differ in terms of diffusion difficulties.

There are regional differences in the benefits of agricultural policy diffusion, considering the industrial structure and climatic suitability characteristics of different regions, as well as the growth characteristics of crops. The motivation of connected leading cadres serving in different regions for the expansion of PA is different. The climatic phenomena that cause regions to be unsuitable for developing PA during the March-June sowing period are mainly high temperature and lack of sunlight, which affects 1,348 county-level areas in the sample, far exceeding the number of county-level areas affected by climate during the July-February sowing period (Zhang et al., 2021). Moreover, March-June is an important sowing period for most grain crops, oil crops, and vegetables (Li et al., 2014), which implies a relatively wider range of exposure to climatic unsuitability during March-June. That is, connected leading cadres whose jurisdictions confront climate unsuitability in March-June will carefully consider whether to expand PA; after all, it may not be economical to invest additional production management costs to cope with climate risks. In addition, in Model (6) of Table 2, the coefficients of the variables gross regional product and the interaction term of the mayor's governing preference and secondary sector output are statistically significant at 1% level. This implies that regions with better economic and secondary sectors could provide sufficient input support for PA, which in turn reinforces the positive influence of connected mayors on PA expansion. However, the economic strength and infrastructure of western regions are relatively weaker (Yin et al., 2019), which makes the expansion of PA more difficult and reduces the motivation of connected leading cadres for PA expansion. Meanwhile, most areas in western China are unsuitable for the expansion of PA. For example, of the 745 counties located in the western region in this study, 645 counties have to face unsuitable climatic conditions during the July-February sowing period, and 671 counties during the March-June sowing period. This means that the agricultural industry in this area does not need to be blindly transformed into PA.

The four Chinese prominent PA development regions - Shandong, Jiangsu, Hebei, and Liaoning provinces—have great differences in PA development history, which is manifested in the differences in technical difficulty and dissemination scope. Shandong and Liaoning provinces are the two major origins of PA in China. Among them, Liaoning province is the largest solar greenhouse area and the key area of PA production, which has formed a large-scale production model that combines multi-seasonal production in solar greenhouses in winter and production in cold sheds in summer (Li et al., 2013). The PA model in Liaoning Province could well cope with the climatic constraints in northern areas (Li et al., 2013; Local customs, 2022). Moreover, Shandong province has become the center of China's greenhouse vegetable production with intelligent solar greenhouses (Ou et al., 2021). As many as seven technology iterations have made Shandong Province very mature in terms of planting technology and management models to support PA. The technical and management advantages of Shandong and Liaoning provinces in terms of PA have made the leading cadres connected with them more motivated to increase PA expansion. However, it is important to note that the "Shouguang vegetables" brand of Shandong Province has been more widely promoted in many places due to the media and the support of government-enterprise cooperation (Chen, 2021), which leads to the possibility of inaccuracy in estimating the influence of leading cadres on PA expansion by just using their connections with Shandong Province. Besides, Jiangsu province is a rapidly developing region for PA in the new era (Jin and Jiang, 2009) and the region has formed a rich cluster area of advantageous industrial in PA, such as the solar greenhouse base in northern Jiangsu province, the steel frame greenhouse base in Jianghuai region, and the intelligent greenhouse base along the coast and river, etc. (Ping et al., 2010). These can provide diverse learning templates for leading cadres connected with Jiangsu Province and enhance their motivation for PA expansion. Lastly, although Hebei Province is the relatively smallest of the four regions in terms of both speed and scale of PA development, it has also formed three major greenhouse vegetable dominant production areas (Han et al., 2017). Since the PA model of Hebei Province still needs to be optimized and its prominent small-scale greenhouse technology does not have outstanding comparative advantages over the other three regions (Gao, 2012), the leading cadres connected with it are less motivated to promote PA technology.

6 Conclusion

The expansion of PA is imperative for future agricultural development. Since 2008, when the Chinese Ministry of Agriculture issued the "Opinions on Promoting the Development of Protected Agriculture" (Agriculture, 2008), PA has become an important direction for agricultural transformation. In China, Shandong, Jiangsu, Hebei, and Liaoning provinces have been areas of rapid development in PA, with the scale of regional PA all far exceeding the national average and playing an important demonstration role in promoting PA technology nationwide.

Based on policy diffusion and official behavior theories, this report scrutinizes the information of leading cadres in 314 prefectural cities in China with data on PA in 1,792 counties for the period 2014–2018. The results show that the leading cadres with governing preferences is critical in promoting relevant policy diffusion. Specifically, mayors connected with Shandong, Jiangsu, Hebei, and Liaoning provinces significantly promote PA expansion, and the scale of PA in county-level areas under these connected mayors is on average 10.8% higher than that of areas under unconnected mayors. Also the mayor's age, level of economic development (*Mprimary*), and agricultural output effect (*lnMpgrp*) have significant positive effects on PA expansion, while the degree of regional industrialization (*Rsgrp*) could reinforce the positive effects of connected mayors on PA expansion. Whereas, the effect of connected municipal party secretaries on PA expansion is not significant, which may be related to the different responsibilities among mayors and municipal party secretaries. In addition, there are geographical differences in PA expansion. This study found that the positive impact of connected leading cadres on PA expansion will be significantly weakened when the areas under their jurisdiction are located in economically underdeveloped western regions or in areas that are climatically unsuitable during the March-June sowing period. Moreover, since the prevalence and difficulty of PA farming technologies in Shandong, Jiangsu, Hebei, and Liaoning provinces vary, there are differences in the motivation of leading cadres connected to each of these four regions to diffuse the relevant technologies. Among them, Shandong and Liaoning provinces, the two major origins of PA in China, have relatively greater positive effects on PA expansion.

In the past 40 years, PA in China has developed rapidly and has made an important contribution to securing people's food needs. This study not only broadens the research field and theoretical understanding of local leading cadres' decision-making behavior and their influence on policy diffusion but also contributes to a deeper understanding of the mechanisms driving farmland conversion in China. In the context of accelerated agricultural modernization, it needs to be noted that the current development of PA still faces obstacles such as low mechanization levels, fragmented land distribution, insufficient scientific and technological innovation, and a lack of professional talents (Takeshima and Joshi, 2019). To this end, reference can be made to our findings that strengthening the connection between leading cadres and regions with better development of PA, especially Shandong and Liaoning provinces, will help to deepen the knowledge of leading cadres in fields such as PA production technology and management models, which in turn would promote the expansion of PA and the transformation of agricultural modernization. Alternatively, if a city wishes to promote policy innovation in a specific area, it may consider strengthening the connections between local leading cadres and regions with successful policy implementation in that area, which would help leading cadres learn from the demonstration regions and also the policy innovations diffusion.

This study does acknowledge several limitations. First, although we spent a great deal of time collecting and quantifying information on officials' career transfers, the way officials establish connections with regions may be through short-term off-site visits, studying central government documents, and media campaigns, in addition to the birthplace and the place where they have served. This makes it difficult to capture all the circumstances under which officials establish connections with regions. Second, during the career transfer process, officials may not always maintain strong connections with all regions, especially those who are transferred because of negative experiences. Therefore, it is not possible to accurately quantify the strength of the connections that officials establish with different regions. In the future, we could try to characterize the connections and the strength of connections between officials and different regions by using spatial weight matrixes and further analyze the impact of officials on the dynamics of policy diffusion. In addition, in-depth interviews or surveys can be combined to analyze the effectiveness of officials on policy diffusion.

Data availability statement

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

Author contributions

ML: Conceptualization, software, methodology, writing. DQ: Supervision, writing—reviewing and editing. TZ: Conceptualization, supervision, writing—reviewing and editing.

Funding

The study was supported by grants from National Natural Science Foundation of China (Grant Nos: 42261144750, 41771189).

Acknowledgments

Our sincere thanks to the National Natural Science Foundation of China [Grant Nos: 42261144750, 41771189], without which this paper would never have come into fruition.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 13 April 2023
DOI 10.3389/fenvs.2023.1115058

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Land Use Dynamics,
a section of the journal
Frontiers in Environmental Science

RECEIVED 03 December 2022
ACCEPTED 27 March 2023
PUBLISHED 13 April 2023

CITATION
He Y, Wu D, Liu Y and Zhu H (2023), Review of research on evaluating the ecological security of cultivated land. *Front. Environ. Sci.* 11:1115058.
doi: 10.3389/fenvs.2023.1115058

Review of research on evaluating the ecological security of cultivated land

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Cultivated land provides fundamental land-related resources, and its ecological security is, thus, an important means of protecting it. The ecological security of cultivated land has emerged as an important and challenging area of research in recent years. In this study, we summarize the progress in research on the evaluation of the ecological security of cultivated land through visual analysis. We review the concepts, characteristics, driving factors, scales and methods of evaluation, technologies, and simulations used in the relevant literature. The results show that while the relevant concept has been preliminarily established, research on the ecological security of cultivated land remains in its infancy, and comprehensive work on the subject is lacking. The Prevalent research has mainly focused on analyzing the current situation, but lacks a dynamic analysis of the driving mechanism of the ecological security of cultivated land based on simulations. This has made it difficult to understand the spatiotemporal mechanism of the ecological security of cultivated land. Future research in the area should discuss the complex driving mechanism of interactions between the social economy system and the ecological system and focus on an integrated model to assess its dynamic spatial and multi-scale characteristics of ecological security of cultivated land because this can inform the theory of protecting cultivated land and the design of plans for land use to mitigate global climate change.

KEYWORDS

ecological security of cultivated land, concept evaluation index system, evaluation scale, evaluation method, model simulation, spatial–temporal evolution, CiteSpace software

1 Introduction

Protecting the area, quality, and ecology of cultivated land is an important aspect of research on land resource management. The area of cultivated land is the basis for producing materials (Tan et al., 2005), its quality is the fundamental guarantee of its productivity (Kong, 2014), and protecting its ecology is the basic requirement of its security. The relevant research has primarily focused on the security of the area and quality of cultivated land instead of its ecology. Assessing the ecological security of cultivated land is not only beneficial for managing the conflict between humans and land to ensure food security and social stability but also important for regional ecological protection and sustainable economic development that can ensure a harmonious society (Zhang and Song, 2012). The ecological security of cultivated land refers to the security of the resource environment, ecological system, and social economy. It is a functional concept relative to the threat posed to the ecology. Researchers have systematically analyzed sustainable land use in various regions at different scales, (Rasul and Thapa, 2003; Beesley and Ramsey, 2009; Aksoy et al., 2022) such as rivers, construction land, grasslands, and wetlands at the national, provincial, municipal, and district levels (Zhao et al., 2002; Li and Lai, 2011; Wang et al., 2011a; Wang et al., 2011b; Xu et al., 2011; Li et al., 2014; Chen, 2017; Zhou et al., 2018; Li et al., 2019; Yang et al., 2019; Zhang et al., 2019). However, current research has not adequately attended to the ecological security of cultivated land. Even the basic concept of the ecological security of land has not yet been clearly described, and methods to assess it remain in their infancy. No unified system of indices or method is available to this end, and a dynamic, multi-factor system to evaluate the ecological security of cultivated land is still elusive (Zheng et al., 2009; Liu et al., 2017). This requires considering an explanation of the concept and its connotations (Xiao et al., 2002; Chen and Zhou, 2005; Zhu, 2008; Zhang and Song, 2012), developing a system of indices to assess it (Gong et al., 2010; Li et al., 2022), and analyzing the relevant circumstances (Zhang and Song, 2012; Wu and Xie, 2019). Research on evaluating the ecological security of cultivated land can inform policymaking on reasonably using and protecting cultivated land and coordinating the health of the ecosystem with sustainable development.

Industrialization and urbanization have caused a decline in the area and quality of cultivated land, an increase in pollution, and the deterioration of the ecological environment. This affects food security and social stability, thus threatening the survival of human civilization. Former Chinese Premier Wen Jiabao noted that "the management of protection for land resources in developed countries has already undergone two stages—the management of its area and quality—and is now undergoing higher levels of development, while the management and protection of cultivated land in China is still in an early stage of development." The deteriorating ecological environment of cultivated land will lead to a sharp reduction in its area and damage its quality (Li et al., 2001). Protecting cultivated land resources, preventing the contamination and destruction of farmlands, and strengthening the assessment of their ecological security are, thus, major issues of widespread concern and daunting problems in research. Peng et al. (2018) observed that "in developing countries such as China, where natural habitats are under pressure from high-intensity human interference during rapid urbanization, only bottom-line thinking about the ecology can yield a win–win solution that balances ecological protection with economic development." In light of the aforestated, in this study, we define the ecological security of cultivated land, review and summarize the main content of research in the area, and suggest directions for future research.

2 Collecting information on the status of prevalent research

Researchers have conducted preliminary studies on the ecological security of cultivated land that provide a sound foundation for evaluating and simulating it. As the amount of literature on the subject continues to grow, much of it can be downloaded for free. We used CiteSpace software to visually analyze research in the area. It is used widely for literature reviews as it can provide useful results (Chen, 2012, 2020; Chen and Song, 2019).

We constructed a dataset of the literature on the ecological security of cultivated land by using multiple sources. It contained publications ranging from December 1994 to March 2023. The papers were drawn from the Web of Science, Scopus, Dimensions, and PubMed databases, which are the most widely used bibliographic databases in research (Visser et al., 2021). Table 1 summarizes the database, which contains information on 1,288 studies.

The results of executing CiteSpace are shown in Figure 1, the overview highlighting the most active areas of the relevant research. Figure 1 provides an overview of the underlying network of references in the area that have often been cited together. The nodes represent the references cited, and the clusters represent concentrations of themes. The degree of concentration may vary widely across clusters, and each cluster is assigned an automatically generated label. The largest cluster, #0 cultivated land protection, is at the center of the network. The second-largest cluster, #1 economic benefits, is located near cluster #0 (see Table 2 for cluster details).

The articles in the constructed database were cited 4,216 times in total, 4,131 times excluding self-citations. Thus, the average number of citations per article was 13.15, and the h-index was 35. These articles belonged to a variety of categories, including environmental sciences, environmental studies, green sustainable science and technology, and ecology and biodiversity conservation. Researchers from China were the most prolific in terms of publication, followed by those in the Americas, Germany, the Netherlands, and India. The Chinese researchers were mainly from the Chinese Academy of Sciences (CAS), the Institute of Geographic Sciences and Natural Resources Research of the CAS, the University of CAS, China Agricultural University, and China University of Geosciences. These authors were funded by the National Natural Science Foundation of China (NSFC), the CAS, the Fundamental Research Funds for Research in Central Universities, the China Postdoctoral Science Foundation, and the National Key Research and Development Program of China. The relevant studies focused on environmental science ecology, science and technology, agriculture, and biodiversity conservation and engineering. The timeline of this research area and important articles on the ecological security of cultivated land are shown in Figure 2 and Table 3, respectively.

The aforementioned timeline of literature on the ecological security of cultivated land shows the area of the circle represents literature records that busted the co-citation rate. CiteSpace identified studies by Liu et al. (2017) in cluster #4 (habitat quality) and Wu et al. (2017) in cluster #5 (land reclamation) as the most noteworthy articles because they had been co-cited by multiple articles. The study by Peng et al. (2018) in cluster #10 (ecological corridors) had the highest citation rate in the ecology of land. The Table 3 shows the publication with the earliest publication date, the highest citation rate, the highest intensity of co-citation, and the most correlation and the latest publication in the field.

2.1 Status of research on the ecological security of cultivated land

Ecological security is an interdisciplinary field involving natural and social sciences. While there is no consensus on the definition of

TABLE 1 Comparison of the sources of data obtained from search queries.

Data source	Website	Articles	Search strategy	Initial
Web of Science	https://clarivate.com/webofsciencegroup/solutions/web-of-science/	368	Full text	1999
Scopus	https://www.scopus.com/search/	530	Title, abstract, and keywords	2000
Dimensions	https://app.dimensions.ai/discover/publication	306	Title and abstract	2000
PubMed	https://pubmed.ncbi.nlm.nih.gov/	84	Best match	1994

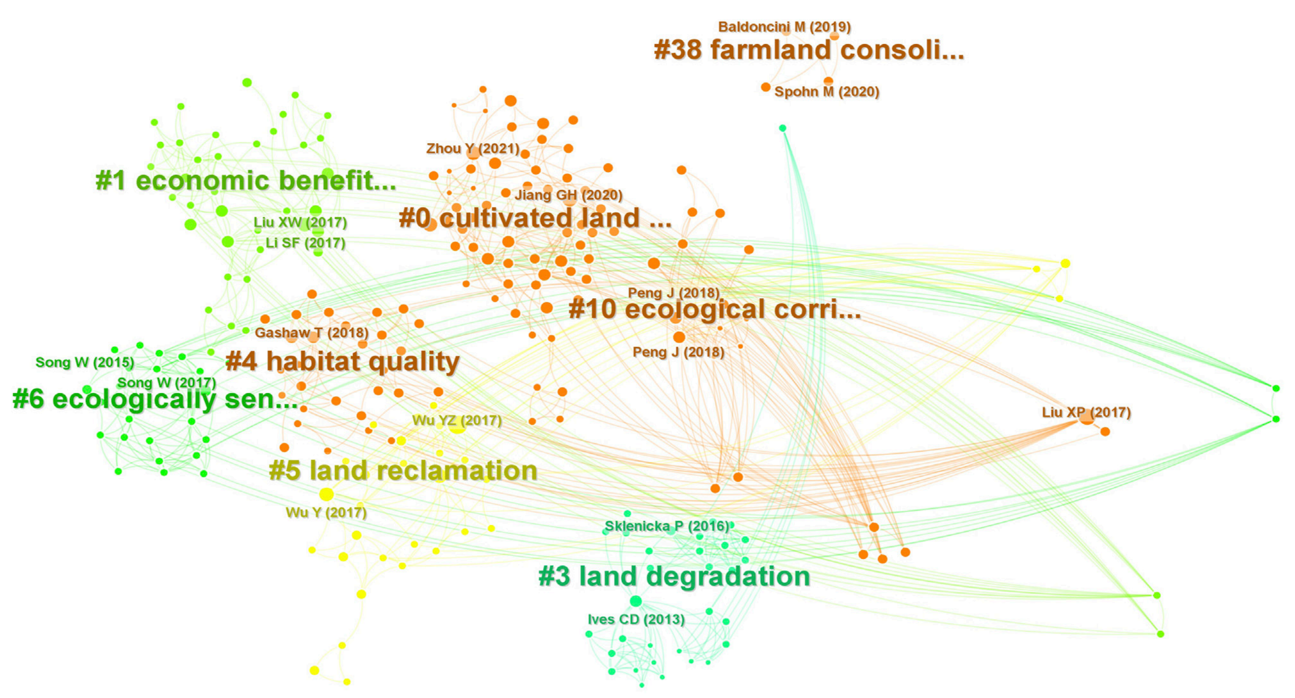

FIGURE 1
Overview of clusters in the ecological security of cultivated land literature.

TABLE 2 Clusters representing themes of research on the ecological security of cultivated land.

Clusters	Label
#0 Cultivated land protection	Sustainable development; ecological security; spatiotemporal variation; driving mechanism; Enshi Autonomous Prefecture | land protection; differentiated control measures; multi-functional assessment; fuzzy set; arable land protection cooperation
#1 Economic benefits	Land use efficiency; sustainable land use; Jiangsu province; coupling coordination; impact factor | threshold model; land utilization; economic belt; Yangtze River
#3 Land degradation	Two-step cluster analysis; peri-urban agriculture; risk identification; environmental management | mountain agriculture; urban growth; environmental perception; central Andes; landscape change
#4 Habitat quality	Human footprint index; landscape model; multi-scenario analysis | scenario simulation; ecosystem service; spatiotemporal analysis; Yellow River basin
#5 Land reclamation	Rapid urbanization; food security; requisition–compensation balance policy; ecosystem services | land protection policy; AHP—entropy method; effect evaluation
#6 Ecologically sensitive suburban area	Karst mountains; land use change; scenario simulation; ecosystem services; influence degree | ecosystem services value; sensitive suburban area; influence degree
#10 Ecological corridors	Ecological security patterns; landscape connectivity; network connectivity assessment; Chongqing municipality; ecosystem services | environmental function; driving forces; spatiotemporal characteristics; landscape pattern evolution; land cover change
#38 Farmland consolidation	Land quality; basic physical; chemical properties; heavy metals | land quality

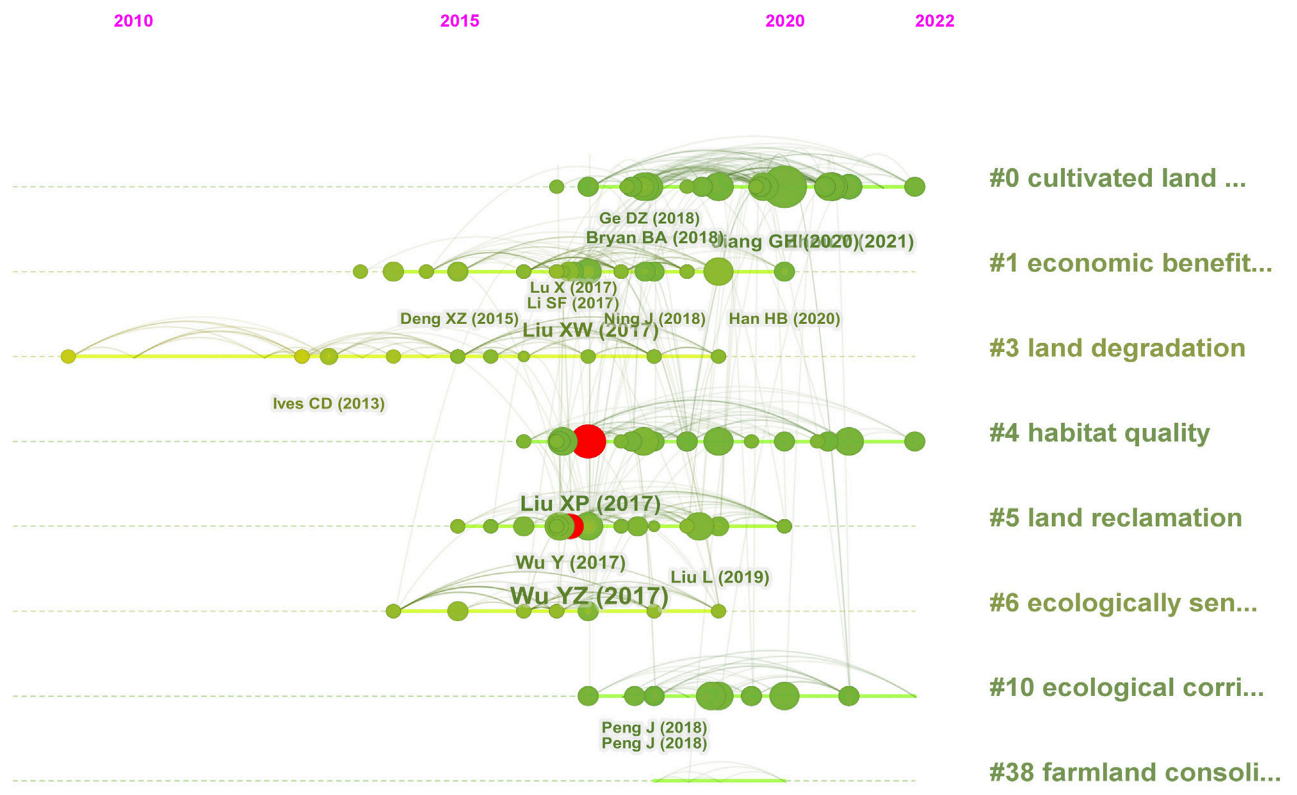

FIGURE 2
Timeline view of literature records on ecological security of cultivated land.

TABLE 3 Overview of important articles.

Author	Article	Journal	Characteristic
Talla, 1994	Population and environment. The era of ecological refugees	Pop Sahel	The earliest relevant literature
Peng et al. (2018)	Linking ecosystem services and the circuit theory to identify ecological security patterns	Science of the Total Environment	The highest-cited literature
Song and Pijanowski (2014)	The effects of China's cultivated land balance program on potential land productivity at a national scale	Applied Geography	The strongest co-citation literature
Liu et al. (2017)	A future land use simulation model (FLUS) for simulating multiple land use scenarios by coupling human and natural effects	Landscape and Urban Planning	The co-citation burst literature
Wu et al. (2017)	Cultivated land protection policies in China facing 2030: Dynamic balance system versus basic farmland zoning	Habitat International	The co-citation burst literature
Wu and Xie (2019)	The variation differences of cultivated land ecological security between flatland and mountainous areas based on LUCC	PLOS One	The most relevant literature
He et al. (2017)	Construction and evaluation of cultivated land ecological security system: A case study in Zhuhai City	6^{TH} ICEESD	The most relevant literature
Li et al. (2022)	Optimizing the use of cultivated land in China's main grain-producing areas from the dual perspective of ecological security and leading-function zoning	International Journal of Environmental Research and Public Health	The latest relevant literature
Zhu et al. (2021)	Land use evolution and land ecological security evaluation based on the AHP–FCE model: Evidence from China	International Journal of Environmental Research and Public Health	The latest relevant literature

ecological security, most scholars claim that it can be understood in both a broad and a narrow sense. The broad sense of ecological security encapsulates people's lives, health, happiness, basic rights, security of living, access to the necessary resources, and their ability to adapt to environmental changes and social order. This, in turn, includes natural ecological security, economic security, and social ecological security that constitute a composite system of ecological security. The narrow sense of ecological security is defined as the safety of the natural and semi-natural ecological systems and pertains to their integrity and overall level of health (Xiao et al., 2002; Chen and Zhou, 2005). The health of an ecosystem is a new concept in environmental management. Normally functioning ecosystems are considered to be healthy, stable, and sustainable because they can maintain their organizational structure, autonomy, and resilience to stress. Unhealthy ecosystems are those with incomplete or abnormal functions and those that are under stress.

Research in developed countries has focused on assessing the ecological health of land and provided a well-defined and complete concept and relevant systems and methods of evaluation. These contributions can be viewed as related to work on assessing the ecological security of land, but most such research has ignored the ecological security of cultivated land. Research on the ecological security of cultivated land in China has roughly undergone three stages of development. It started in the 1990s, but the importance of ecological security truly came to the fore after the heavy floods in Sanjiang in 1998 and the dust storm in northern China in 2000. During this period, such scholars such as Yu et al. (1999) investigated regional patterns of ecological security. This can be regarded as the first phase of research on the ecological security of cultivated land. Subsequently, Peng et al. (1996) and other scholars reported basic research on assessing the ecological environment, constructed a system of evaluation to this end, and conducted empirical analyses on China. This can be viewed as the second stage of research in the area. With the growing realization of the importance of the ecological environment of cultivated land, research has gradually come to focus on the security of cultivated land (Zhang, 2006). This includes assessing the ecological security of cultivated land (Li and Lai, 2011; Wang et al., 2011a; Wang et al., 2011b; Xu et al., 2011; Peng et al., 2018) and making predictions based on simulations (Xu et al., 2007). This is the third and current stage of research in the area.

2.2 Status of research in developed countries

It is generally acknowledged that the concept of "ecological security" appeared in the 1980s. Earlier studies on the subject focused on analyzing the concept and its significance (Wen, 2008). The relevant research in developed countries began with assessments of the health of the ecosystem. As early as in 1941, Aldo Leopold presented the concept and connotation of the health of land and applied it to assess its function. Since then, research on the ecological system and problems of environmental safety has gradually developed (Xiao et al., 2002). The meaning of changes in ecological security was first given by Lester R. Brown, a famous American environmentalist. He redefined the concept of national security in 1977 by claiming that "now, the threat to security is less from relations between countries, and more from the relationship between man and nature" (Brown et al., 1981). From 1983 to 1987, the United Nations World Commission on Environment and Development formulated its report called "Our Common Future," which systematically analyzed the major economic, social, and environmental problems facing humanity. The report set "sustainable development" as the basic platform to protect and develop environmental resources and meet the needs of current and future generations. It recommended a series of policy objectives and action plans and used the term "environmental security" (World Commission on Environment and Development, 1987). In 1989, the International Institute for Applied Systems Analysis formally proposed the concept of ecological security (Chen and Zhou, 2005). In the early 1990s, the United States, Russia, the European Union, and other countries added "environmental security" or "ecological security" to the main targets of their national security strategies. In August 1991, the "National Security Strategy Report" of the United States was the first to incorporate environmental security into the national interest. Steve Lonergan and Norman Myers developed and promoted the concept of ecological security at a very early stage. Lonergan discussed the relationships of the environment and ecological security with sustainable development (Lonergan, 1999). Myers claimed that ecological security is ecological degradation caused by wars for regional resources and global environmental threats, which, in turn, are linked to a lack of economic and political security (Myers, 1989). Gro Harlem Brundtland, the former Norwegian prime minister and chair of the World Commission on Environment and Development, Boutros Boutros-Ghali, the former secretary general of the United Nations, and Al Gore, the former vice president of the United States, are all pioneers of the development and promotion of ecological security as well. They claimed that ecological security arises from the concepts of ecological threat and risk. Humans bear the main responsibility for this ecological threat, and ensuring ecological security is necessary for society, political powers, and the global community and is an important part of social stability, national security, and public security (Herrmann et al., 2003; Foley et al., 2005). The "Global Ecological Security Civic Treaty" was mooted at the 1996 Earth Convention and has since been signed by more than 2 million people from over 100 countries. It is the first international consensus on ecological security. The treaty is based on ecological security, sustainable development, and ecological responsibility and strives for coordination among the benefits and obligations of members and organizations. The United Nations organized the World Summit on Sustainable Development in 2002 in Johannesburg, South Africa. It focused on the problem of global ecological safety and promoted research on the issue (Espejel et al., 1999; Lee, 1999; Smith et al., 1999). Research on the microcosmic analysis of ecological security in developed countries has focused on two aspects. One is the risks posed to ecological security by genetic engineering, and the other is the influence of the use of chemical fertilizers on the health and security of the agricultural ecosystem (Alipbeki et al., 2020a; Alipbeki et al., 2020b). Research in the 21st century has shown that direct measurements, network analyses, and model simulations are necessary to assess ecological security. These need to be wedded with technologies to assess the ecology of the landscape, such as remote sensing and the Geographic Information System, to comprehensively understand the functional process of ecological security.

In conclusion, research on ecological security in developed countries has focused on regional ecological security and sustainable land use at the macroscopic and microscopic level. It has covered the relevant concepts, theoretical systems, methods and indices of evaluation, and dynamic monitoring.

2.3 Status of research in developing countries

2.3.1 Definition of the concept

The concept of the ecological security of cultivated land was proposed only recently. Many researchers have provided varying accounts and interpretations of it based on their academic background. Zhao et al. (2002) proposed that the environmental effects of the security of land use should be used as a prototype of the ecological security of cultivated land, where this includes soil erosion, land desertification, and degradation in the quality of soil. Such negative environmental effects are caused by the development and use of cultivated land. Zhang (2006) noted that the ecological security of cultivated land refers to a scenario in which the ecological environment, which is the reliable basis for the existence and development of humankind, unthreatened, or less threatened, by damage and imbalance. Under this condition, the ecological system is stable and balanced and has an abundance of natural resources such that the ecological environment of cultivated land is pollution free, unmolested, and unthreatened. Zhu (2008) further developed the concept by noting that the ecological security of cultivated land resources, including the security of resources and the environment, the ecological system, and social and economic security, means that the ecosystem has a normally functioning structure that can ensure sustainable development to satisfy social and economic needs. The environmental security of cultivated land means that the resource and biological environments of cultivated land are safe or unthreatened. The security of the ecosystem of cultivated land includes the safety of its internal structure. The socioeconomic security of cultivated land involves the functions and features of cultivated land resources to realize the security of society and the economy. The social and economic safety of cultivated land is the ultimate target of ensuring its ecological security (Peng et al., 2004; He et al., 2017). Wang Jun (2009) claimed that the ecological security of cultivated land means to ensure that the ecological environment is less affected, or unaffected, through the mutual coordination of the natural, economic, and social systems at a certain time and spatial scale. The ecological system of cultivated land functions normally in this case. We define the ecological security of cultivated land as the organic unity of its area, quality, and ecological environment at a certain time and spatial scale. Because the recycling of materials, energy conversion, and the flow of information change constantly between the biological and environmental systems of the ecological security of cultivated land, they are always interrelated (Figure 3). The ecological security of cultivated land is a higher direction of security and development than area, quality, and ecological environment. The ecological security of cultivated land is a state of functions related to ecological threats and is a relative and dynamic concept. It has the features of regionalism, systematics, dynamics, imperceptibility, regulation, externality, publicity, and strategies. The concept of the ecological security of cultivated land can promote high-quality development to achieve environmental and social economy benefits (see Table 4).

2.3.2 Analyzing features of the ecological security of cultivated land

The ecological security of cultivated land has its own distinctive features. Zhang (2006) pointed out that cultivated land has the features of artificiality, irreversibility, chronicity, and integrality. Zhu (2008) observed that it also has the features of commonality, crypticity, and strategy. The commonality of the security of cultivated land resources is largely determined by externalities. Because cultivated land has the function of ensuring food security, it is considered to be a kind of public product. Changes in its ecological security are slow and subtle. It takes a long time for cultivated land to change from a safe state to an unsafe state, because of which this transition is difficult to detect. By the time we identify this process, the land already undergoes a qualitative change. Ecological security is an important part of the national security system as it has strategic significance for sustainable social and economic development. The ecosystem of cultivated land plays an important role in the overall ecosystem as well. Wang Jun (2009), noted the comprehensive and important features of the ecological security of cultivated land. They include many aspects as well as influential, natural, ecological, economic, and social factors. These factors interact with and influence one another to render ecological security complex. Analyses at different temporal scales have shown that it undergoes dynamic evolution.

2.3.3 Analyzing factors driving the ecological security of cultivated land

In their analyses of the factors driving the ecological security of cultivated land, Chinese researchers have paid special attention to theoretical analyses but have ignored comprehensive, systematic, and empirical analyses (Zhu, 2008). Zhao et al. (2002) concluded that the main factors influencing the ecological security of cultivated land are population growth, social and economic development, patterns of land use, technological development, environmental optimization, and environmental policy. Zhang (2006) claimed that regional topography and natural disasters influence the ecological safety of the Three Gorges Reservoir Area in Chongqing. Zhu (2008) proposed dividing the factors influencing the ecological security of cultivated land in China into direct and indirect factors. Economic is the direct factor referring to the financial support for agriculture, and the social awareness of protecting cultivated land is the indirect factor. The indirect factor also plays a key role in influencing the ecological security of cultivated land and determines the degree of ecological security. Wang (2009) claimed that factors influencing the ecological security of cultivated land include natural, economic, and social factors. He analyzed factors influencing the ecology of Shijiazhuang based on dynamic changes in the area, quality, and ecological environment of cultivated land. Prevalent research has shown that the ecological security of cultivated land is affected by many aspects of natural and human activities at different scales. Separately analyzing the relevant conditions, their ranges of influence, and their dynamic processes can help reasonably explain and predict the mechanism of changes in the ecological security of cultivated land.

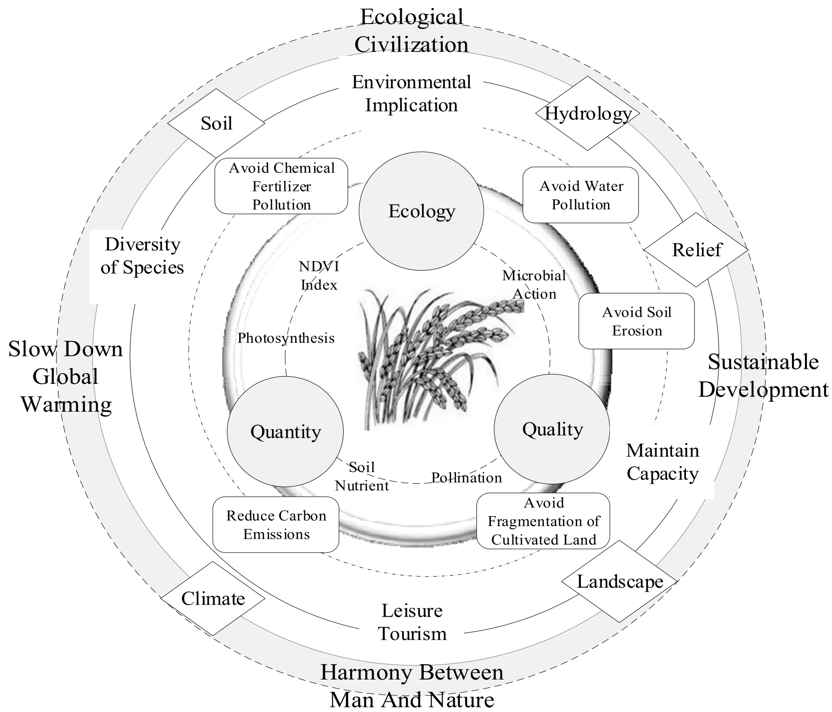

FIGURE 3
Composition structure of a system for ecological security of cultivated land.

TABLE 4 Benefits of ecological security of cultivated land to the environment and social economy.

Benefits to environment	Benefits to social economy
• Ecological life support	• Leisure tourism
Circulating and purifying air and water	• Culture of farming
Fixation and circulation of nutrients	• Education and research
Formation and maintenance of soil • Diversity of life Growth of plants Growth of animals	• Use-related benefits Production of food • Non-use-related benefits
	Interest in land Aesthetic Spiritual
• Global climate change Carbon storage Decomposition of microorganisms above and below the ground Improved absorption of fertilizers	• Future value Food security guarantee Sustainable development Social stability

2.3.4 Scales of evaluating the ecological security of land

Scale refers to the size of the ecosystem (spatial scale) or its temporal dynamics (temporal scale) (Fu et al., 2001). Using different scales yields different levels of patterns and processes and their rules of interaction. This ultimately influences the scientific and practical aspects of research (Lu and Fu, 2001; Ma et al., 2005). Ecological security can be considered at multiple scales. Understanding the scales of the ecological security of cultivated land is the most effective means of evaluating it and an important prerequisite for establishing a system for it (Lee, 1999). The health of the ecosystem of cultivated land differs at various temporal stages of the evolution of its structure and function. Energy flow and the recycling of materials in each component in different stages maintain a stable and dynamic balance, and the health of the ecosystem of cultivated land changes with the environment (Cui and Yang, 2003). Research that uses "time points" can be used to quickly evaluate the status and characteristics of cultivated land, but different reference indexical values often create wide differences in the results. Research characterized by "time periods" can be used to easily define the dynamic changes in cultivated land, but this strategy yields uncertain results when the data are incomplete (Cui and Yang, 2003). Research on the ecological security of cultivated land at different spatial scales considers different objects, such as the individual, the overall population, the community, the ecosystem, and the landscape. This, in turn, requires a suitable spatial scale to establish relations with macroecological and microecological problems (Zhang and Ren, 2005). Large-scale studies help better understand the status of ecological security in general, while small-scale research helps explore the mechanisms of ecological security and their specific performance in great detail. Therefore, the relevant research should not only consider the spatiotemporal unity of the ecological security of cultivated land but also examine the spatiotemporal differences in it based on the characteristics of the object of study to improve the authenticity of the evaluation. Scale conversion is connected at different levels by time or space and involves transforming data from one scale to another. From the perspective of evolution, conclusions from relatively large-scale studies can be applied to small-scale studies. Assessment at the spatial scale involves the transformation of data from the national, provincial, and regional levels (Zhao et al., 2002; Zhu, 2008) to the prefecture level at the mesoscale, as well as at the county level and lower levels (Wang, 2009). The temporal scale of evaluation ranges from a single year to a continuous period of several years (Zhu, 2008). However, if the research scale of ecological security of cultivated land is too large, many details may be lost. This also leads to a lack of consideration of regional differences (Li et al., 2001).

2.3.5 Methods and technologies of evaluation

Studies assessing the ecological security of cultivated land have evolved from conducting qualitative to quantitative research in China in recent years. Qualitative research provides a theoretical basis to this end, while quantitative evaluation can identify the state and level of the ecological security of cultivated land to render it measurable. Using both qualitative and quantitative methods to assess the ecological security of cultivated land is, thus, the natural direction of development of prevalent research. Currently used methods include fuzzy comprehensive evaluation, the comprehensive index-based method, system dynamics-based methods, methods to determine the ecological carrying capacity, and those based on artificial neural networks (Zuo et al., 2002; Liu et al., 2011). Wang Jun (2009) quantified indices to assess the ecological security of cultivated land by using a linear dimensionless method according to data obtained from statistical yearbooks and field surveys. The BP neural network was used to evaluate the ecological security of cultivated land in Shijiazhuang City, and the results were simulated in MATLAB 6.5. The authors divided states of the ecological security of cultivated land into five levels: poor, middle, good, very good, and ideal. Wu and Xie (2019) used the pressure support framework as a system of indicators of assessment and used an improved BP neural network model to capture dynamic spatiotemporal changes in the ecological security of cultivated land in Yuxi City from 2005 to 2015. However, Most of the research studies on the ecological security of cultivated land in China still use statistical yearbook data for quantitative analysis, and the combination of 3S spatial analysis technology and geo-statistics for evaluation is relatively rare.

2.3.6 Systems of indices for evaluation

The main idea underlying the formulation of a system of indices to assess the ecological security of cultivated land is to identify the relationship between the ecological environment and society. Such a system of indices is a large and complex system. Social consensus on a standard system of indices of evaluation to this end remains elusive. The most frequently used methods include the pressure–state–response indexical system, the exposure–response analysis system, the system of indices of the landscape, and the system of indices of sustainable development. The system of comprehensive indices, which is integrated into the aforementioned systems, was built on the basis of ecological and soil sciences, thus attending to social, economic, and landscape-related data. This is believed to represent the future direction of development in research on the evaluation of the ecological security of cultivated land (Liu et al., 2011). The choice of indices of evaluation is based on the principles of scientificity, integrity, dominance, availability, operationalism, universality, dynamism, and stability. Zhu Hongbo created a system of indices to assess the ecological security of cultivated land according to the factors influencing its connotations. It consisted of six indices representing directly influential factors, five representing indirectly influential factors, and five indicators of socioeconomic impact. Wang Jun (2009) created a system of indices for evaluation based on a target layer, an index layer, levels of indices, and 22 indices of evaluation. The natural factors influencing the ecological security of cultivated land included the *per capita* area of cultivated land and unused area of land *per capita*, forest coverage, and the area occupied by paddy fields. The economic factors considered included the GDP growth rate, the ratio of expenditure on agriculture, the *per capita* net income of farmers, and the use of chemical fertilizer on units of cultivated land. Social factors influencing the ecological security of cultivated land included the level of urbanization, the index of pressure of cultivated land, population density, and the rate of population growth. Wen et al. (2007) proposed a system of indices that considered the quality of the climate and soil, geologic landforms, and the area of cultivated land through 19 indices. The authors proposed one factor of ecological safety to comprehensively account for important factors. Social and economic factors alone cannot satisfy the need for assessing the ecological security of cultivated land. Researchers, thus, need to pay more attention to the area of cultivated land and factors related to the quality of the ecological environment.

2.3.7 Simulation and prediction

As the current status of the ecological security of cultivated land cannot meet the needs of society, research on predicting its state through simulations has become prevalent. Xu et al. (2007) proposed an early warning system for the ecological security of cultivated land. This involves a qualitative evaluation of the ecological environment, forecasts of its expected status in the future, and the generation of a warning if detrimental changes in it are expected that can hinder the coordinated development of the ecological environment and the social economy. The authors used Microsoft Visual Studio.NET as the platform to develop an early warning system of this kind for Anhui Province in China. They also developed indicators of early warning and a method to set the level of warning based on four considerations: the fertility of soil in farmlands, the quality of the environment, its health, and output. However, this system is merely a prototype and requires further research and development. Moreover, it is based only on a single index such that it does not consider the complicated relations between the factors of assessment. Furthermore, it cannot simulate the regional ecological security of cultivated land resources or the trends of changes in them owing to a lack of support based on 3S technology. Therefore, the simulation and prediction of the ecological security of cultivated land should actively absorb research achievement of related disciplines and aim to develop from single-factor to multi-factor comprehensive simulation.

2.3.8 Measures to protect the ecological security of cultivated land

As developing countries are in a period of rapid economic development, protections for cultivated land play an important role in ensuring national food security, social stability, security of the regional ecological environment, and the overall coordinated development between urban and rural areas for them (Cai, 2001; Song and Ouyang, 2012). This determines the state of the ecological security of cultivated land. Song et al. (2014) noted that protections for the ecology of cultivated land should be guided by the multi-functional demands of urban and rural residents for cultivated land, and more attention should be paid to conserving resources and protecting the environment through a series of measures related to land use and land management. This can ensure that the area, quality, and spatial pattern of cultivated land are suitable for the protection of farmland ecology and coordinated development. Fu and Tan (2005) considered problems related to the ecological security of cultivated land in Hubei Province in China from 1995 to 2004. Peng (2013) considered the comprehensive ecological security of cultivated land in the Jianghan Plain in China from 2001 to 2010. He noted that measures to ensure the ecological security of cultivated land are designed to publicize them and improve public awareness, influence the relevant regulations, establish early warning systems for them, strengthen the ecological restoration and reconstruction of cultivated land, prevent agricultural pollution, establish a mechanism for ecological compensation, control the population, encourage people to coordinate and develop reserved resources of cultivated land, carry out land consolidation and mining, and achieve a balance between the area and quality of cultivated land. Chen (2011) developed five measures according to the state of risk to the ecological security of cultivated land in Shandong Province in China from 1999 to 2008: increasing funds for the ecological protection of cultivated land, improving the level of agricultural mechanization, strengthening the management of investment in agricultural and ecological security, and establishing a legal system for the conservation of cultivated land. Zhang (2006) proposed a system for protecting the regional ecology of cultivated land. He applied it to a reservoir in Fengdu County in Chongqing Province of China by considering institutional guarantees, funding, and technological security. Protecting the ecology of cultivated land involves satisfying multi-functional demands for its utilization, natural and socioeconomic conditions, and multi-level and multi-dimensional spatial and functional forms to develop the corresponding measures.

3 Progress of research on evaluating the ecological security of cultivated land

The importance of research on the ecological security of cultivated land is widely recognized in both developed and developing countries. Researchers have analyzed problems related to the ecological security of cultivated land by using theories and methods with the aim of sustainable development. These research studies have laid an important foundation for further systematic work in the concerned area. However, due to the complexity of the object of study and the limitations incurred by an imperfect theoretical system and methods of research, the problems described in the following section continue to require attention.

3.1 Focus on mesoscale research of cultivated land ecological security

Owing to the different spatial and temporal scales used in research, the various mechanisms of assessing the security of the ecosystem of cultivated land yield different results. Due to the complexity of the ecological system of cultivated land, many studies in the past focused on studies conducted at the macroscopic spatial scale and short temporal scales. Furthermore, the observations and scale of research used are singular, and there is a lack of research at the mesoscale, which makes it difficult to understand the regional ecological security of cultivated land based on its overall dynamic characteristics and mechanism of evolution. With the development of high-resolution remote sensing technology and depth-monitoring technology, it is now possible to study synchronous data from a large area at multiple scales (Zuo et al., 2003; Li and Pan, 2010). The mesoscale may be the most suitable to research the ecological security of cultivated land.

3.2 Establishing a system of indices to assess the ecological security of cultivated land

Researchers have proposed several systems of indices to assess the ecological security of cultivated land according to their aims in different areas of study (Gao et al., 2008; Gao et al., 2017; Lai et al., 2023). These systems involve a number of natural elements, such as the topography, vegetation, landscape index, landscape function, and ecological indicators, as well as non-natural factors, such as the society, economy, and pressure from human activities. However, an evaluation system with a large number of indices complicates the problem of ecological security and impedes its evaluation. Thus, as few indices as possible should be used as representatives so that they can be controlled to focus on the most important issues. The evaluation indices should be chosen by attending to social and economic factors, the area and quality of the cultivated land, and the ecological environment. Future studies need to discuss the complex mechanism of interactions between the social economy system and the ecological system according to the chain of "risk identification–external influence–degree of safety–mechanism of influence—regional prevention" to build a system of indices to assess the ecological security of cultivated land.

3.3 Improving current methods and developing new ones

Research on and technologies for assessing the ecological security of cultivated land are still in their infancy. Models of evaluation methods to this end, in particular, need to be updated in future works. At present, static methods of evaluation are the main ones, while dynamic methods of evaluation are scarce. Quantitative models of mathematical evaluation are more frequently used than models of spatial evaluation. Therefore, future research on assessing the ecological security of cultivated land should seek to combine mathematical models and 3S technology to build models. Furthermore, methods of dynamic evaluation should be considered based on static evaluation. Researchers should identify the key factors and processes for the ecological security of cultivated land.

3.4 Strengthening research on the ecological security of cultivated land and climate change

The proposal for the ecological security of cultivated land plays an important role in slowing down global warming. According to the 2006 report of the IPCC, different methods of farming influence changes in the carbon pool, for example, irrigation and dryland or greenhouse farming. These farming methods directly affect climate change (Giardina and Ryan, 2000; Simon et al., 2006). The change of ecological security of cultivated land not only affects human activities, but also has a profound impact on climate change. How to quantitatively analyze the impact of ecological security of cultivated land on climate change is not only a scientific problem in the field of climate change, but also a difficult problem in the field of surface system science.

4 Conclusion

Our review of the relevant research here has shown that most studies have considered the security of land resources as the object of research, while few authors have considered the ecological security of cultivated land. Moreover, most studies have used static analyses instead of dynamic analyses based on simulations. Recent works have considered typical regions in case studies from the perspective of the area of cultivated land resources, changes in the quality of land, mechanisms driving these changes, pattern of the landscape, and the relationship between social and economic development. However, these studies have overemphasized the safety of and prevention of damage to the area and quality of cultivated land resources but have ignored the ecological security of cultivated land. Evaluating this is an important means of monitoring risks to the ecological environment, managing ecological resources, and providing early warnings in case of changes in the quality of the ecological environment. With rapid urbanization and modernization in recent decades, the conflict between the ecosystem of cultivated land and human activities has become increasingly prominent. The use of cultivated land for non-agricultural construction, the use of chemical fertilizers, and the pollution of soil by residues from heavy metals are serious problems that deteriorate the quality of cultivated land and fragment its landscape. This enhances the risk of the ecological degradation of the land. The ecological risks of cultivated land will lead to increased carbon emission, water pollution, and soil erosion that affect food security and social stability. Moreover, social progress has led to a transformation in the significance of cultivated land from its traditional function of production to ecological functions. The concept of ecological security has been introduced can improve the quality of cultivated land and achieve sustainable development. Therefore, investigating the ecological security of cultivated land can help relieve the tension between humans and nature, modernize its management, and provide a reference for decision making and future planning in agriculture.

5 Discussion

The evaluation of the ecological security of cultivated land has emerged as a new field of research in recent years. No uniform system of evaluation is yet available as a reference, and few theories and methods have been developed for it. However, the subject is very important. In this study, we systematically reviewed the literature on the ecological security of cultivated land and suggested directions for future theoretical and practical research in the area. We have made the following contributions to research in the area: 1) We introduced the general state of research in the field, including the prominent researchers, countries of origin of research, research institutions, and important studies. This helped determine the status of research on the ecological security of cultivated land in general. We used CiteSpace software to visualize the results of our survey. 2) We identified the concept, phases, and characteristics of the ecological security of cultivated land and the factors driving it. We also systematically discussed the relevant scales of evaluation, methods and technologies, systems of indices, methods of simulation and forecasting, and measures of protection. 3) We provided directions for future research in the area. We believe that the factors of the ecological security of cultivated land are an important basis for the formulation of measures and policies on land resource management, land use structure optimization, land use transformation, and ecological protection.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

YH, DW, YL, and HZ contributed to the conception and design of the study. YH organized the database. YH performed the statistical analysis. YH wrote the first draft of the manuscript. YH, DW, YL, and HZ wrote sections of the manuscript. All authors contributed to manuscript revision and read and approved the submitted version.

Funding

This work was supported by Program of National Natural Science Foundation of China, (No.41971184); Team Project of Natural Science Foundation of Guangdong Province, (No.2018B030312004); Guangdong Planning Office of Philosophy and Social Science under the project "Disciplinary Co-projects for 2020 under the 13th Five-Year Plan" (No. GD20XYJ32); 2022 Guangdong Province Ordinary University Characteristic Innovation Category Project (Humanities and Social Sciences category) (2022WTSCX087); 2022 Tertiary Education Scientific Research Project of Guangzhou Municipal Education Bureau (No. 202235269); the Department of Education of Guangdong Province, under the "2020 Research Project under the 13th Five-Year Plan, Special Research Area on the Construction of Guangdong—Hong Kong—Macao Greater Bay Area" and "The Silk Road" (No. 2020GXJK199); 2021 Curriculum Ideological and Political Education Construction Project "land use planning" of Guangdong Institute of teaching management of colleges and universities (No. x-kcsz2021158); Guangzhou University Project "On-campus research projects (research category)" (No. YJ2021007); 2022 Guangzhou Higher Education teaching quality and teaching reform project (No. 2022JXTD001); and Renmin University of China: the special developing and guiding fund for building world-class universities (disciplines).

Acknowledgments

The authors would like to acknowledge WD and ZH, Guangzhou University, for valuable discussion and assistance in interpreting the significance of the results of this study. They also thank the editor and reviewers for their valuable comments and suggestions.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 16 June 2023
DOI 10.3389/fenvs.2023.1172537

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RECEIVED 23 February 2023
ACCEPTED 17 April 2023
PUBLISHED 16 June 2023

CITATION
Hua J and Li R (2023), Impact of land loss on academic performance among rural adolescents in China: based on cognition-investment-performance framework.
Front. Environ. Sci. 11:1172537.
doi: 10.3389/fenvs.2023.1172537

Impact of land loss on academic performance among rural adolescents in China: based on cognition-investment-performance framework

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Introduction: As an exclusive group resulting from land requisition and demolition during the process of urbanization, the education of children belonging to land-loss farming families has received worldwide attention. However, few studies have explored the mechanisms and effects of land loss on adolescents' academic performance.

Method: Using 5,133 family samples in 2014 and 3,810 family samples in 2018 from China Family Panel Studies (CFPS), this study employed the PSM-DID and KHB models to explore the impact of land loss on the academic performance of rural adolescents.

Results: The findings indicate that compared to non-land-loss families, the academic performances of adolescents in the land-loss families were lower. Additionally, land-loss families have a lower awareness of educational value. This verifies the logical mechanism of "land loss→ family education cognition→ family human capital investment→ adolescents' academic performance." Gender differences exist in the negative effects of land loss on adolescents' academic performance; land loss has a greater impact on boys.

Discussion: The government should strengthen the training system for land-loss farmers, improve the social security system and state of female-led families, and focus on boys affected by land loss.

KEYWORDS

land loss, academic performance, teenagers, gender difference, rural revitalization

1 Introduction

Adolescence is the most important phase in human capital formation (Heckman and Kautz, 2014), and the human capital of rural adolescents is pivotal in the sustainable development of the national economy and society. The academic performance of adolescents helps them realize their own human capital accumulation and evade the intergenerational transmission of poverty (Bai et al., 2019; Nong et al., 2022; Victora et al., 2022). However, the academic performance of urban and rural adolescents is still not at par (Wang et al., 2021; Liu and Helwig, 2022). According to the China Family Panel Studies (CFPS) 2020 data, only 20.46% of educated adolescents in rural families in China had "excellent" scores in both Chinese and mathematics. Therefore, there is an increasing awareness of the importance and urgency of improving the academic performance of rural adolescents to promote balanced educational development (Agger et al., 2018; Boeren, 2019). The Chinese government has issued a series of documents, including the "No. 1 Central Committee Document of 2021" and "Opinions of the State Council on the Implementation of the Rural Revitalization Strategy," aimed at achieving the equalization of rural and urban education by prioritizing its development and improving the quality of education and teaching. However, despite the efforts of governments at all levels to promote the rural education guarantee mechanism, they still fail to effectively achieve the comprehensive and high-quality development of rural education.

In China, investment in education generally includes investment in both public education and family education. Compared with public government educational investment, family private educational investment has a greater influence on the resources and growth environment that enable children's development and adolescents' academic performance (Ghanney, 2018; Kim et al., 2020; Fretwell, 2021). Previous studies mainly focused on the relationship between parental involvement and children's academic performance, particularly discussing the influence of parents' educational expectations (Cross et al., 2019; Pinquart and Ebeling, 2020), personal characteristics (such as education and income levels) (Assari and Caldwell, 2019; Poon, 2020), personal status (such as social status and economic status) (Duan et al., 2018; Tan et al., 2020), and specific behaviors (such as parenting style and parent-child interaction) (Talin et al., 2021; Toor, 2021) on children's academic performance. These studies are useful for understanding the relationship between parental involvement and children's academic performance. However, research on the structural factors, such as parental background, influencing the mechanism of educational inequality is scant. With the comprehensive deepening of China's urban-rural integration process, a significant amount of rural collective land has been converted to urban construction land, resulting in a rapidly growing number of land-loss farmers as an exclusive group (Xie, 2019; Wang et al., 2020; Bao et al., 2021). Consequently, in terms of the right and quality of learning, the academic performance of Chinese land-loss farmers' adolescent children is adversely affected, along with the process of achieving balanced educational development.

Among the studies on the impact of land loss on the academic performance of adolescents, some studies have explored the inequality of educational opportunities between land-loss farmers and urban families based on time (Tang and Li, 2021). Additionally, some scholars have used social conflict patterns to analyze the impact of land acquisition on children's education (Le and Nguyen, 2020). However, this literature is based on the direct impact of land loss on children's education, while neglecting the invisible link between land loss and children's academic performance. Therefore, to fill this gap, the current study investigates the influencing variables of adolescents' academic performance based on the logical framework of "land loss→ family education cognition→ family human capital investment→ adolescents' academic performance" to further explore the path of improving the academic performance of rural adolescents.

As a major life event, land loss has a significant effect on farmers' life choices. It leads to a loss of permanent income from land for rural families (Li et al., 2018; Coulibaly and Li, 2020; Tuan, 2021), making it rational for them to seek non-farm work in cities. However, this often leads to frequent unemployment and unstable employment (Liu, 2020; Kang and Li, 2022), increasing the mental pressure on parents. This can result in them prioritizing their own livelihood decisions over those of their adolescent children's in terms of quality of learning motivation and learning rights, owing to their social status and emotional changes (Xu, 2020; Palit, 2022), and this pressure forces land-lost farmers to reduce expenditures on their adolescents' education. In addition, the mental stress caused by the loss of land may cause land-lost farmers to adopt inappropriate parenting methods (McLeod and Shanahan, 1993) and the intergenerational transfer of family culture can result in internalization of adolescents' learning attitude and academic expectations, thus affecting family education cognition and affecting their children's educational views (Yang, 2021; Furukawa Marques and Lagier, 2022). Land loss may affect adolescents' academic performance through parenting methods (education cognition) and human capital investment of the families.

In summary, this study focuses on identifying the impact of land loss on the academic performance of rural adolescents and analyzes the heterogeneous effects of differences in the gender of decision makers and the gender of adolescents. The innovative aspect of this study is as follows: 1) It tests the influence of the mechanism of land loss on rural adolescents' academic performance based on the adolescent stage of human capital investment, according to the logic of "land loss → family education cognition → family human capital investment → adolescents' academic performance; " 2) To improve the robustness of the research results, this study improves the covariates by setting the family characteristic variable, the household economic variable, and the community variables, while progressively enriching the dependent variable in terms of educational cognition, family human capital investment, and academic performance; 3) It thoroughly investigates the impact of land loss on the academic performance of adolescents based on the gender of decision makers and adolescents' gender differences and analyzes the reality of "gender equality" in the education of adolescents in rural China. The research content and implications of this article are also applicable to developing countries with similar national conditions and resource endowments as China, intending to serve as a lesson to these countries, particularly for issues related to land-loss.

The remainder of this paper is organized as follows: Section 2 introduces the theoretical framework, whereas Section 3 introduces the data sources, variable selection, and model construction. Section 4 presents the empirical results. Section 5 provides an in-depth discussion of these results. The conclusions and related policy recommendations are presented in Section 6.

2 Theoretical framework and hypotheses

The role of parents in family education is crucial. Parents can shape children's values and behaviors through parent-child relationships and family interactions, ultimately impacting their learning achievement through educational expectations (Veas et al., 2019; Pinquart and Ebeling, 2020). However, urbanization has disrupted the lifestyle of land-lost farmers, forcing them to expend most of their energy and time on finding and adapting to new work, which can have negative impacts on the mental state of family members (Ding et al., 2020; Wu and Wang, 2021; Han et al., 2022). As a result, land-lost farmers equate children's education with formal schooling, and thus, neither devote time nor energy to it. Moreover, the education level of land-lost farmers is generally low, and they often lack the necessary skills to engage in non-agricultural industries, which limits their job opportunities during urban expansion (Liu et al., 2018; Memon et al., 2019). Their education level and employment environment limitations lead to the choice of livelihood strategies and their educational concepts and behaviors are limited by the cultural concept of "content with the *status quo*." This leads to a misestimation of the urban-rural integration process of education and neglecting the adolescents' education.

In terms of research methods, these studies have mostly focused on qualitative descriptions of cases in specific regions and lack empirical analyses based on nationally representative sample data in China. Although some studies have used Tobit, Tobit-IV, and DID models to explore the effects of court environment on adolescents' academic performance, they have been unable to well attenuate the effects of unobservable intergroup differences on assessment results. In terms of research content, while these studies have demonstrated an implicit link between landlessness and adolescents' human capital, they have not thoroughly examined the impact of landlessness on academic performance indicators that directly reflect individual human capital status and require a careful analysis of the causal mechanisms involved. Land acquisition can be considered the loss of the most important capital for livelihood (Xu et al., 2019; Le and Nguyen, 2020). Limited by resource endowment, land-lost farmers struggle to secure suitable employment in cities, leading to changes in their family's main income patterns. This difficulty in compensating for the loss of direct income through capital or labor after the loss of land often results in a decline in family income (Belay and Mengistu, 2019; Kojin, 2020). Given that family income significantly affects education consumption expenditure (Jabar et al., 2021; Wei et al., 2021), land-lost farmers struggle to afford the cost of their children's education when family economic conditions are severely constrained. As a result, children from many land-lost families fail to enter high-quality schools, negatively impacting their academic performance due to lack of investment in their education, as compared to those from non-land-lost families. Therefore, we propose the following hypotheses:

H1: The academic performance of adolescents from land-loss families is worse, and earning females have a promoting effect on the academic performance of children.

H2: Compared with non-land-loss rural families, land-loss farmers have lower levels of family education cognition and lower human capital investment.

The emotional and mental impact of land loss on farmers (Duncan et al., 2019; Chen, 2020) hinders their ability to guide their children, resulting in neglect of their children's studies and negatively impacting their academic performance. According to the family division of labor theory, housework and childcare responsibilities are exclusive to women (Koster et al., 2022). Among land-lost farmers, female employment can provide additional economic support to the family and alleviate the economic pressure caused by land loss. Moreover, compared to fathers, mothers are more likely to allocate family resources to children's education and related expenditures (Yunxia and Xinrong, 2020; Wang and Cheng, 2021; Koster et al., 2022), which can improve their adolescents' academic performance. Additionally, boys are more competitive and sensitive to their environment than girls (Bully et al., 2019; Shi et al., 2021). In a land-lost environment, boys are more affected by the non-learning-oriented surroundings and their academic performance is lower compared to girls. Therefore, we propose the following hypothesis:

H3: Among the children, the academic performance of boys is affected more by land loss than that of girls.

Figure 1 illustrates the pathways by which land loss affects adolescent academic performance.

3 Data, variables, and methods

3.1 Data

The data used in this study were obtained from the 2014 and 2018 CFPS databases established by the China Center for Social Sciences Investigation (ISSS) of Peking University. The sample covered 25 provinces, municipalities, or autonomous regions. All family members identified in the 2010 baseline survey and their future biological or adopted children were permanently tracked as genetic members of the CFPS. Four types of questionnaires were used: community, family, adult, and children, and the survey objects included all family members in the sample households. The land situation and human capital investment status of the interviewed households was investigated in detail. The study focused on rural families with adolescent children aged 10–15 and excluded families with incomplete land acquisition information or without school-aged children. After data cleaning, there were 5,133 household samples in 2014, with 312 belonging to the treatment group (land was expropriated before 2018) and the remaining 4,821 in the control group. In 2018, the sample consisted of 3,810 households, with 295 belonging to the treatment group (land acquired during the current period), and the remaining 3,515 in the control group.

3.2 Variables

The aim of this study was to investigate the impact and mechanism of land loss on the academic performance of rural adolescents. The core treatment variable was *treated,* which denoted whether land was acquired. Before applying the PSM-DID model, the treatment variable was constructed based on whether the rural family experienced land acquisition in 2018 and not 2014. If so, it was included in the treatment group with a value of 1. If a rural household did not experience land expropriation in both 2014 and 2018, it was set in the control group with a value of 0. According to Table 1,

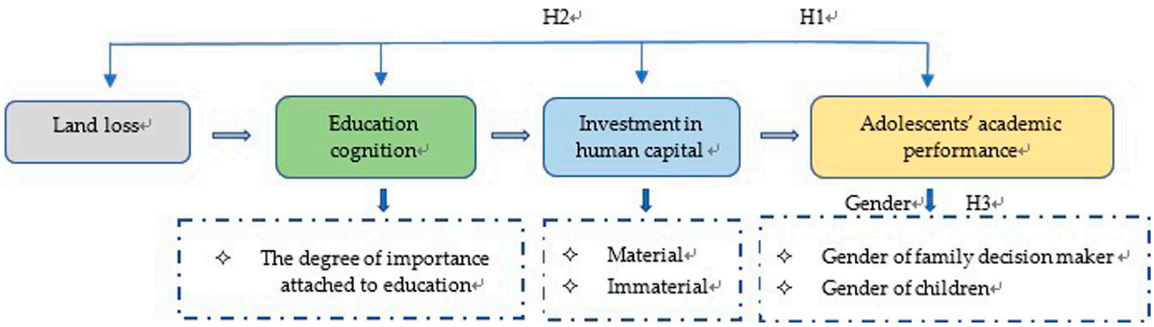

FIGURE 1
Theoretical framework.

6.78% of the rural household land in the sample was expropriated.

Following the analytical logic of "land loss→ family education cognition→ family human capital investment→ adolescents' academic performance", the dependent variables in this study were divided into three levels: 1) *childsave* and *saving*, which represented the family's emphasis on education, for analyzing the impact of land loss on family education cognition; 2) *spend* and *talk* for measuring human capital investment in education expenditure and non-material human capital investment in children's learning, respectively; 3) *class rank*, *grade rank*, *Chinese*, and *math,* which represented the adolescents' academic performance, for analyzing the effects of land loss on the accumulation of adolescent human capital, and on the relative and absolute evaluation of academic performance.

Multiple factors can affect adolescents' academic performance. In addition to the key variable of land acquisition, this study selected covariates based on the literature (Zhihua et al., 2015; Junlong, 2017; Haochen, 2019). We included 13 indicators, including family characteristics, family economy, and community variables. Table 1 presents the variables and descriptive statistics used in this study.

3.3 Methods

Y was set as the outcome variable (academic performance of adolescents) influenced by the loss of land. Intuitively, the effect of land loss on the academic performance of adolescents from rural families is as follows:

$$\boldsymbol{ATT} = \boldsymbol{Y}_{t1} - \boldsymbol{Y}_{t0}, \quad (1)$$

where ATT represents the effect of land loss on rural families (treatment effect), Y_{t0} represents the outcome variable values of families in the treatment group in 2014, and Y_{t1} represents the 2018 outcome variable values for households in the treatment group. However, Eq. 1 may be biased because even if the land is not expropriated, the value of Y may change with time; that is, Eq. 1 ignores the change of time trend. Thus, Eq. 2 is used to correct this bias:

$$\boldsymbol{ATT} = (\boldsymbol{Y}_{t1} - \boldsymbol{Y}_{t0}) - (\boldsymbol{Y}_{t1f} - \boldsymbol{Y}_{t0}), \quad (2)$$

where Y_{t1f} represents the outcome variable in 2018 that could not be observed if the treatment group had not undergone land acquisition, and $(Y_{t1f} - Y_{t0})$ represents the change in the academic performance of adolescents in the treatment group without land acquisition, which is not observable.

Assuming that the treatment and control groups have the same time trend, Eq. 3 is used for DID estimation:

$$\boldsymbol{ATT} = (\boldsymbol{Y}_{t1f} - \boldsymbol{Y}_{t0}) - (\boldsymbol{Y}_{c1} - \boldsymbol{Y}_{c0}), \quad (3)$$

where Y_{c1} represents the outcome variable in the control group in 2018, and Y_{c0} represents the outcome variable of the control group in 2014. Eq. 3 is a common DID estimation method that must satisfy the common trend assumption. The validity of the estimation depends on whether $(Y_{t1f} - Y_{t0})$ and $(Y_{c1} - Y_{c0})$ are equal.

PSM is a commonly used method to study land issues, but PSM-DID has the advantage of further attenuating the effect of unobservable intergroup differences on assessment results compared to PSM alone. If the assumption of a common trend is not satisfied, "selection bias" of the samples will occur, and the reliability of the model results will be compromised. PSM constructs counterfactual events by finding samples from the control group that have similar characteristics to those in the treatment group. It thereby overcomes "selection bias," and by combining PSM with the DID method, we can control for non-observable, time-dependent between-group differences, and address endogeneity. Overall, PSM-DID can reduce or eliminate the difference in time trends between the two types of households by estimating propensity scores for dislocated and non-dislocated households through observable covariates and matching each dislocated household with its closest non-dislocated household, solving the endogeneity problem caused by sample selection. In this study, we adopted the PSM-DID method to effectively identify and evaluate the "treatment effect" using STATA 17.0 software (Fan and Zhang, 2021; Zhang et al., 2022).

This study implemented the differential PSM model proposed by Heckman et al. (1998) to investigate the impact of land loss on rural families' human capital investment and adolescents' academic performance. Prior to estimation, the two types of families were matched based on propensity scores. Specifically, propensity scores

TABLE 1 Variable selection and descriptive statistical analysis.

Variables		Name	Description	Mean	Std. dev	Min	Max
Treatment variable		Treated	Did you go through eminent domain: yes = 1, no = 0	0.068	0.251	0	1
Covariates	Family characteristic variables	agep	Age of the household head	35.396	8.477	20	84
		agep2	Square of the age of the head of the household	1,324.728	679.560	400	7,056
		gender	Gender of the household head: female = 0, male = 1	0.496	0.500	0	1
		edumax	Highest level of education in the family: illiteracy/semi-illiteracy = 1, primary = 2, junior high = 3, senior high = 4, junior college = 5, bachelor's degree = 6, master's degree = 7, doctorate = 8 ± = 7	3.124	1.556	1	8
		fs	Number of books in the home: none = 0, 1–10 books = 1, 11–20 books = 2, 21–50 = 3, 51–100 = 4, 101–500 = 5, 501–1,000 = 6, more than 1,000 = 7	1.715	1.761	0	7
		young	Number of adolescents aged 10–15 years	1.524	0.696	1	6
		old	Number of family members aged 60 years and above	0.846	0.901	0	2
	Household economic variables	fincome1_per	Per capita net household income (yuan)	10,990.170	11,040.840	0	168,625
		total_asset	Household net worth (yuan)	307,931.200	916,488.600	−704425	50,000,000
		fm	Whether anyone is self-employed: yes = 1, no = 0	0.094	0.292	0	1
	Community variables	cg	Time to provincial capital (hours), the most common mode of transportation used by people from the villages to go to the provincial capital of the province, such as by car, train, plane, etc.	5.408	5.857	0	60
		ch	Proportion of migrant workers (%)	37.852	22.209	0	90
		provcd	eastern region = 1, central region = 2, western region = 3	2.073	0.837	1	3
Dependent variables	Cognition of family education	childsave	Whether you save money for children's education: no = 0, yes = 1	0.540	0.500	0	1
		saving	Money saved for children's education in the past 12 months (yuan)	8,882.285	13,841.060	0	200,000
	Household investment in human capital	talk	How often you talk to your child about school: never = 1, rarely (once a month) = 2, occasionally (once a week) = 3, often (2–4 times a week) = 4, often (5–7 times a week) = 5	2.985	1.207	1	5
		spend	Total Expenditure on education in the past 12 months (yuan)	2,925.297	3,622.548	0	36,300
	Academic performance of adolescents	class rank	Last midterm and final exam class ranking (%): top 10% = 1, 11%–25% = 2, 26%–50% = 3, 51%–75% = 4, bottom 24% = 5	2.804	1.696	1	5
		graderank	Last midterm and final exam grade ranking (%): top 10% = 1, 11%–25% = 2, 26%–50% = 3, 51%–75% = 4, bottom 24% = 5	3.216	1.850	1	5
		math	Math score: poor = 1, medium = 2, good = 3, excellent = 4	2.293	1.048	1	4
		chinese	Chinese score: poor = 1, medium = 2, good = 3, excellent = 4	2.266	0.992	1	4

were calculated for land-loss and non-land-loss households based on observable household characteristics (covariates). Then, each land-loss household was matched with the closest non-land-loss household, thereby eliminating the time trend of two types of families. Subsequently, the treatment effect was calculated using the DID method as per Eq. 3. The specific steps taken are as follows:

First, PSM processing was performed. A logit model was constructed for regression with *treated* as the explained variable, and a group of new observed samples were obtained by "1:1 nearest neighbor" matching method.

$$\boldsymbol{logit}\,(\boldsymbol{treated} = \mathbf{1}) = \boldsymbol{\alpha_0} + \boldsymbol{X_{it}\beta} + \boldsymbol{\varepsilon_{it}}, \quad (4)$$

where $Treated$ indicated whether rural households were treated by land acquisition, if so $treated = 1$, else $treated = 0$. X_{it} represented the covariate, including the family characteristic variable, family economic variable, and community variable. ε_{it} was the residual.

Second, the difference model was constructed as:

$$\boldsymbol{Y_{it}} = \boldsymbol{\alpha} + \boldsymbol{\gamma treated} + \boldsymbol{X_{it}\delta} + \boldsymbol{\mu_i} + \boldsymbol{\vartheta_t} + \boldsymbol{\varepsilon_{it}}, \quad (5)$$

where γ represented the treatment effect of the policy, X_{it} was the covariate, μ_i was an individual fixed effect, ϑ_t was a time fixed effect, and ε_{it} was the residual term. The dependent variables were divided into three levels: family education cognition, human capital investment and adolescents' academic performance. The hypotheses will be tested sequentially in the empirical analysis.

To identify the mechanism of land loss on the academic performance, this paper draws on Breen et al. (2013) and uses the KHB mediation effects test to test whether education cognition and family human capital investments affect adolescents' academic performance. For the test of mediating effects, the traditional test of mediating effects is only applicable to linear models and cannot test nonlinear models. The KHB mediation effect test can effectively decompose linear and nonlinear regression models of the mediating effects.

4 Results

4.1 The influence of land loss on the academic performance of adolescents

4.1.1 Test of balance

An important prerequisite for the application of the PSM-DID method is to balance the control variables. The balancing hypothesis requires that the bias between the matched treatment and control groups is less than 5%, or that the t-test results show no significant difference between the matched treatment and control groups. Table 2 presents the balance test results for the control variables before and after matching. The mean standard error of the control variables decreased from 16.1% to 3.8% after matching. The Pseudo R2 value, which measures the goodness of fit of propensity score regression, was low after matching. The p-value of the joint significance test of the coefficients of the control variables was 0.994, indicating that the coefficients of the control variables were jointly significant before matching, and the null hypothesis that the coefficients of the control variables were jointly 0 could not be rejected after matching. To ensure the quality of matching between samples, the kernel density plots were further plotted after obtaining the propensity scores to examine the common support domain after sample matching (see Figure 2). It can be seen that there is a large range of overlap between the propensity scores of the experimental and control groups after matching, and most of the observations are in the common range of values. The above test results demonstrate that this study has well-matched land-lost families and non-land-lost families, the common support assumption is satisfied, so the PSM-DID model is applicable to this study.

4.1.2 Benchmark regression results

Table 3 presents the results of land loss on the academic performance of rural adolescents. Models 1 to 4 use class rank, grade rank, Chinese score, and math score, respectively, as the dependent variables, and include land-loss variables and covariates. The first two columns analyze the academic performance differences between land-loss families and non-land-loss families, while the last two columns show the differences in single subject scores of adolescents. According to Models 1 and 2, after controlling for other variables, the land-loss variables are all significantly positive at the 5% significance level, suggesting that the achievement ranking of adolescents from land-loss families is lower than that of non-land-loss families. Model 3 shows that the coefficient of the land-loss variable is −0.7352, which is significantly negative, indicating that compared to the non-land-loss families, the Chinese scores of the adolescents from land-loss families are lower. Model 4 shows similar results, with the math scores of the land-loss families being lower than those of the non-land-loss families. Furthermore, combining Models 3 and 4, it can be concluded that loss of land has a greater impact on the performance in Chinese of adolescents in rural families. Therefore, Hypothesis 1 is confirmed, suggesting that when rural families face the high external risk of land expropriation, the physical health and mental states of parents are affected, and this negative effect is transmitted across generations, leading to a reduction in academic achievements and performance of adolescent girls.

4.2 Mechanism analysis

4.2.1 The influence of land loss on the family value cognition

According to the analytical logic of "land loss→ family education cognition→ family human capital investment→ adolescents' academic performance," Table 4 presents the results of the PSM-DID model to assess the impact of land loss on rural family education cognition (the degree of emphasis on adolescents' education). The coefficients of land-loss variables in Models 5 and 6 are −0.3516 and −0.2118, respectively. This indicates that land-loss families have a lower awareness of saving for their children, and the amount of money saved is significantly lower than that of non-land-loss families, which implies that the loss of land significantly reduces the cognition of the educational value for rural families.

TABLE 2 Balance test results of control variables before and after matching.

Variable	Unmatched matched	Mean treated	Mean control	Bias%	T-value	*p*-value
gender	U	0.496	0.495	0.200	0.030	0.972
	M	0.496	0.508	−2.300	−0.260	0.794
agep	U	36.130	35.414	8.200	1.340	0.181
	M	36.130	36.342	−2.400	−0.270	0.789
agep2	U	1,383.900	1,326.400	8.300	1.340	0.180
	M	1,383.900	1,405.800	−3.100	−0.340	0.734
edumax	U	2.943	3.108	−11.300	−0.030	0.974
	M	2.943	3.036	−6.400	−0.360	0.723
fs	U	27.385	13.259	26.700	4.620	0.000
	M	27.385	34.261	−13.000	−0.850	0.397
young	U	1.584	1.531	6.700	1.210	0.228
	M	1.584	1.525	7.400	0.830	0.409
old	U	0.859	0.861	−0.200	−0.030	0.974
	M	0.859	0.887	−3.100	−0.360	0.723
lnfincome1_per	U	9.457	8.867	61.700	8.880	0.000
	M	9.457	9.458	−0.100	−0.020	0.984
lntotal_asset	U	12.431	12.091	32.100	5.120	0.000
	M	12.431	12.444	−1.100	−0.130	0.895
fm	U	0.130	0.869	13.800	2.410	0.016
	M	0.130	0.1260	1.200	0.130	0.896
cg	U	25.107	23.957	13.200	2.070	0.038
	M	25.107	25.147	−0.500	−0.050	0.958
ch	U	17.500	19.722	−22.700	−3.460	0.001
	M	17.500	17.582	−0.800	−0.100	0.923
provcd	U	2.130	2.091	4.500	0.740	0.461
	M	2.130	2.193	−7.400	−0.870	0.387
Pseudo R2	U	0.068	—	—	—	—
	M	0.005	—	—	—	—
LR chi^2	U	156.130	—	—	—	—
	M	3.640	—	—	—	—
P > chi2	U	0.000	—	—	—	—
	M	0.994	—	—	—	—

Possibly, rural families are devastated after the loss of land, and their living standards significantly decrease. Rural families may prioritize their survival and may be unable to devote enough time and energy to children to alleviate material hardship, which has negative consequences for child development (Brooks-Gunn et al., 2013; Desmond and Kimbro, 2015).

4.2.2 The impact of land loss on the family human capital investment

Table 5 presents the PSM-DID estimation results of the impact of land loss on the human capital investment of rural families. In Model 7, the coefficient of land-loss variable is 0.668, which is significant at the 1% level, indicating that compared to families whose land is not expropriated, families who have lost

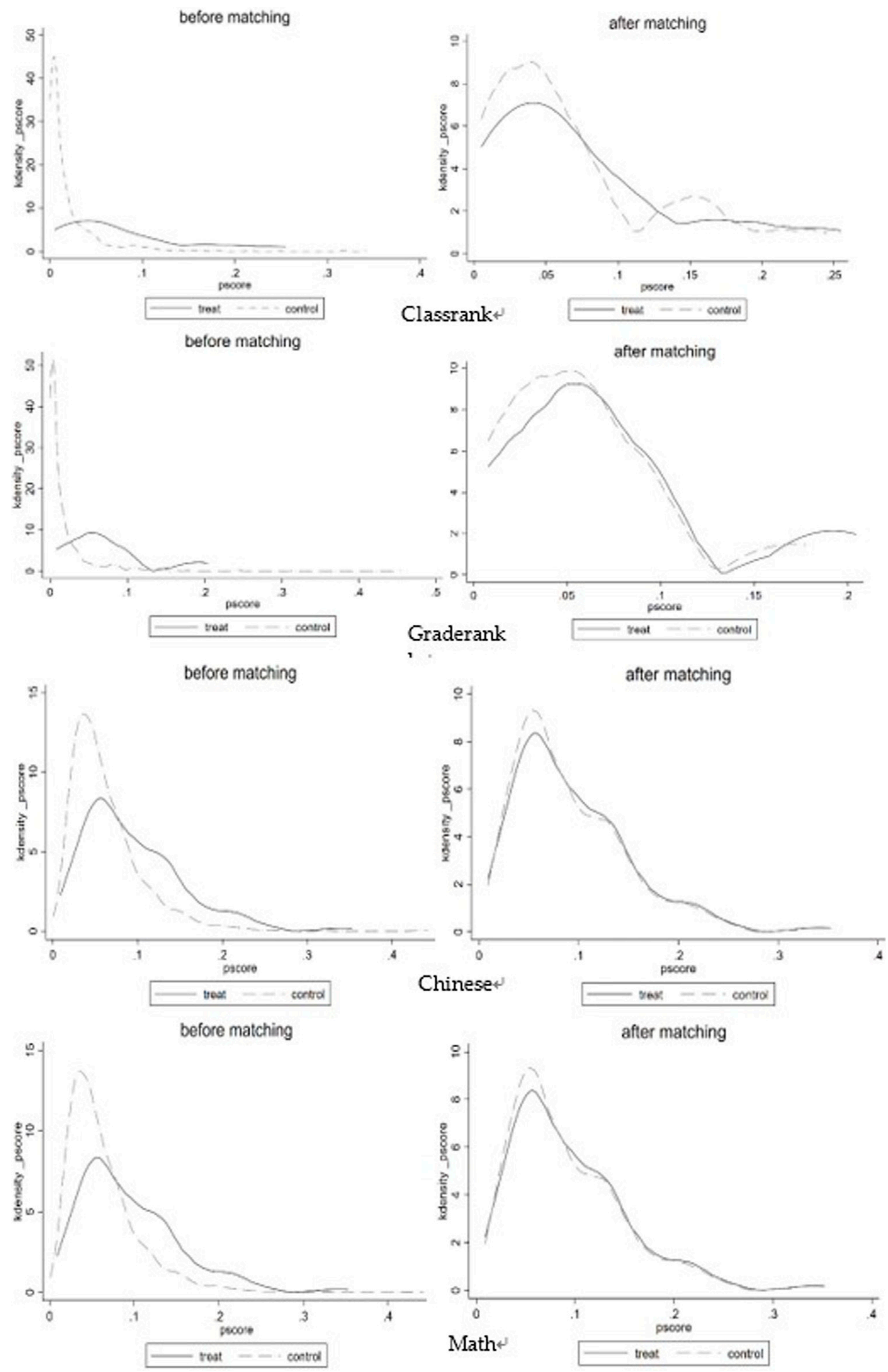

FIGURE 2
Kernel density of adolescents' academic performance before and after matching (1:1 Nearest Neighbor Matching).

their land talk less frequently to their children about school and pay less attention to their children's school conditions. This is because rural families face external risks due to land expropriation and must choose a new livelihood, causing parents to devote more time and energy to employment and relax their focus on their children's study requirements and discipline. In Model 8, the variable of land loss is significantly negative. After land loss, families' adolescent education

TABLE 3 Influence of land-loss on the academic performance of adolescents.

Variables	(1)	(2)	(3)	(4)
	Classrank	Graderank	Chinese	Math
treated	2.610**	2.888**	−0.735***	−0.675**
	(2.444)	(2.359)	(−2.611)	(−2.390)
gender	−0.835***	−0.964***	−0.787***	−0.810***
	(−3.975)	(−4.205)	(−7.323)	(−7.521)
agep	1.336***	1.349***	1.047***	1.054***
	(16.193)	(16.031)	(27.375)	(27.503)
agep2	−0.013***	−0.013***	−0.010***	−0.010***
	(−14.396)	(−14.200)	(−22.520)	(−22.585)
cg	−0.010	−0.010	−0.004	−0.004
	(−0.833)	(−0.789)	(−0.710)	(−0.661)
ch	−0.015	−0.019*	0.002	0.001
	(−1.359)	(−1.683)	(0.339)	(0.188)
lnfincome1_per	0.478***	0.531***	0.225***	0.222***
	(2.721)	(2.955)	(2.788)	(2.743)
lntotal_asset	0.209*	0.128	−0.171***	−0.172***
	(1.842)	(0.973)	(−3.025)	(−3.049)
fm	−0.692**	−0.729**	−0.118	−0.112
	(−2.051)	(−2.082)	(−0.627)	(−0.595)
fs	0.018***	0.017***	0.006***	0.005***
	(6.834)	(6.214)	(4.942)	(4.538)
young	0.079	0.042	0.186**	0.221***
	(0.465)	(0.230)	(2.360)	(2.792)
old	0.489***	0.549***	0.531***	0.538***
	(3.707)	(3.914)	(7.281)	(7.367)
edumax	−0.259***	−0.217**	−0.119***	−0.113***
	(−2.778)	(−2.049)	(−3.262)	(−3.091)
provcd	−0.350***	−0.388***	−0.136**	−0.157**
	(−2.591)	(−2.694)	(−2.046)	(−2.354)
Adj. R^2	0.231	0.246	0.269	0.271

Note: t value in parentheses; $***p < 0.01$ $**p < 0.05$ $*p < 0.1$.

TABLE 4 Impact of land loss on the family education cognition.

Variables	(5)	(6)
	Childsave	Lnsaving
treated	−0.352***	−0.212**
	(−11.117)	(−2.396)
gender	−0.022*	0.063
	(−1.829)	(0.737)
agep	0.009**	−0.048*
	(2.024)	(−1.705)
agep2	−0.0001	0.0003
	(−1.552)	(1.052)
edumax	0.029***	0.027
	(7.052)	(0.814)
fs	0.002***	0.0007*
	(16.505)	(1.708)
young	0.045***	−0.057
	(5.078)	(−1.007)
old	−0.002	0.034
	(−0.246)	(0.583)
lnfincome1_per	0.118***	0.025
	(13.056)	(0.409)
lntotal_asset	0.038***	0.126***
	(6.095)	(2.758)
fm	−0.057***	0.262*
	(−2.693)	(1.911)
cg	−0.003***	−0.008
	(−4.669)	(−1.602)
ch	−0.003***	0.013***
	(−4.161)	(2.830)
provcd	0.030***	0.170***
	(4.014)	(3.211)
Adj. R^2	0.116	0.060

Note: t value in parentheses; $***p < 0.01$ $**p < 0.05$ $*p < 0.1$.

expenditure decreases, which is 0.22 units lower than that of families without land loss. These results are consistent with the findings in the literature (Leventhal and Newman, 2010; Brooks-Gunn et al., 2013; Desmond and Kimbro, 2015). Therefore, Hypothesis 2 is thus confirmed.

4.2.3 Land loss, human capital investment, and adolescent academic performance

To further verify the existence of a behavior-shaping mechanism between land-loss status and adolescents' academic performance, this section presents mechanism tests based on the KHB method (Breen et al., 2013) following the logic of "land loss→ family education cognition →family human capital investment→ adolescents' academic performance". Models 8 and 9 (as presented in Table 6) verify the relationship between family education cognition and family human capital investment. Model 8 was a base model that contained only the control variables. Model 9 added a variable to measure the value of family education. The results of Model 9 show that after adding the variable of family education cognition, the coefficient of the land-loss variable

TABLE 5 Impact of land loss on the household human capital investment.

Variables	(7)	(8)
	Talk	Lnspend
treated	0.668***	−0.222*
	(0.207)	(−1.953)
gender	−0.176*	0.102
	(0.103)	(0.928)
agep	0.335***	−0.028
	(0.047)	(−0.706)
agep2	−0.004***	0.0003
	(0.0006)	(0.734)
edumax	−0.005	0.137***
	(0.038)	(2.628)
fs	0.003***	−0.001
	(0.0007)	(−1.390)
young	0.108	−0.164**
	(0.069)	(−2.514)
old	0.092	0.005
	(0.066)	(0.073)
lnfincome1_per	0.287***	0.068
	(0.067)	(0.900)
lntotal_asset	0.081	0.073
	(0.052)	(1.324)
fm	−0.077	0.009
	(0.183)	(0.057)
cg	−0.008	0.002
	(0.006)	(0.238)
ch	−0.013**	−0.004
	(0.005)	(−0.617)
provcd	−0.079	−0.238***
	(0.063)	(−3.515)
Adj. R^2	0.058	0.052

Note: t value in parentheses; $^{***}p < 0.01$ $^{**}p < 0.05$ $^{*}p < 0.1$.

TABLE 6 Results of KHB mediated effects test.

Variables	(8)	(9)	(1)	(10)
	Lnspend	Lnspend	Classrank	Classrank
treated	−0.222*	−0.193**	2.610**	2.405**
	(−1.953)	(−1.985)	(2.444)	(2.025)
gender	0.102	0.022	−0.835***	−0.423
	(0.928)	(0.446)	(−3.975)	(0.317)
agep	−0.028	0.016	1.336***	0.994***
	(−0.706)	(0.738)	(16.193)	(0.164)
agep2	0.0003	−0.0002	−0.013***	−0.010***
	(0.734)	(-0.804)	(−14.396)	(0.002)
edumax	0.137***	0.063**	−0.259***	0.055
	(2.628)	(3.400)	(−2.778)	(0.150)
fs	−0.001	−0.000	0.018***	0.005*
	(−1.390)	(−0.092)	(6.834)	(0.002)
young	−0.164**	−0.132***	0.079	0.302
	(−2.514)	(−4.066)	(0.465)	(0.221)
old	0.005	0.002	0.489***	0.243
	(0.073)	(0.049)	(3.707)	(0.193)
lnfincome1_per	0.068	0.213***	0.478***	0.121
	(0.900)	(6.582)	(2.721)	(0.255)
lntotal_asset	0.073	0.009	0.209*	0.063
	(1.324)	(0.361)	(1.842)	(0.173)
fm	0.009	−0.058	−0.692**	0.414
	(0.057)	(−0.671)	(−2.051)	(0.593)
cg	0.002	0.000	−0.010	−0.006
	(0.238)	(0.007)	(−0.833)	(0.017)
ch	−0.004	0.001	−0.015	−0.037**
	(−0.617)	(0.559)	(−1.359)	(0.017)
provcd	−0.238***	−0.347***	−0.350***	−0.412**
	(−3.515)	(−11.623)	(−2.591)	(0.202)
lnsaving	—	0.078***	—	—
	—	(3.446)	—	—
lnspend	—	—	—	4.581***
	—	—	—	(0.399)
Adj. R^2	0.052	0.093	0.231	0.393

Note: t values are in parentheses; $^{***}p < 0.01$ $^{**}p < 0.05$ $^{*}p < 0.1$.

decreases compared to the base model and is significant at the 5% level. This indicates that the negative effect of land loss on adolescents' academic performance can be alleviated by improving families' perception of educational value. Moreover, Models 1 and 10 were used to verify the relationship between family human capital investment and adolescents' academic performance. Model 10 included education expenditure to measure family human capital investment in comparison to the basic Model 1 with just the control variables. The results of Model 10 show that the coefficient of the land-loss variable significantly decreases compared to that in Model 1, and the coefficient of *lnspend* variable is significantly positive, indicating that the negative pass-through effect of land loss on adolescents' academic performance can also be effectively compensated by the

TABLE 7 Gender heterogeneity of household decision makers.

Variables	Classrank		Graderank		Chinese		Math	
	Man	Woman	Man	Woman	Man	Woman	Man	Woman
Treated	2.971***	2.438***	2.986*	2.529***	−1.013**	−0.845*	−0.932**	−0.429
	(2.154)	(2.361)	(1.914)	(0.359)	(−2.535)	(−1.712)	(−2.331)	(−1.078)
Family characteristic variables	controlled	controlled	controlled	controlled	controlled	controlled	controlled	controlled
Household economic variables	controlled	controlled	controlled	controlled	controlled	controlled	controlled	controlled
Community variables	controlled	controlled	controlled	controlled	controlled	controlled	controlled	controlled

Note: t value in parentheses; ***p < 0.01 **p < 0.05 *p < 0.1.

TABLE 8 Gender differences of adolescents.

Variables	Classrank		Graderank		Chinese		Math	
	Boy	Girl	Boy	Girl	Boy	Girl	Boy	Girl
Treated	4.129***	1.566	4.051**	1.483	−1.114**	−0.797**	−0.695*	−0.670*
	(2.339)	(1.124)	(2.229)	(0.877)	(−2.251)	(−2.029)	(−1.715)	(−1.692)
Family characteristic variables	controlled	controlled	controlled	controlled	controlled	controlled	controlled	controlled
Household economic variables	controlled	controlled	controlled	controlled	controlled	controlled	controlled	controlled
Community variables	controlled	controlled	controlled	controlled	controlled	controlled	controlled	controlled

Note: t value in parentheses; ***p < 0.01 **p < 0.05 *p < 0.1.

increase in human capital investment. It can be preliminarily concluded that the academic achievement difference of adolescents from land-loss families is affected by their cognition of educational value, the scale of educational resources, and their own learning requirements (Grossman et al., 2011; Liu and Xie, 2015).

4.3 Analysis of heterogeneity

This section continues the discussion on the relationship between land loss and academic performance of adolescents from rural families from the gender perspective. Table 7 presents the sub-sample regression analysis of the academic performance of adolescents, factoring in the gender differences of family decision-makers. The analysis shows that land loss has a negative impact on adolescents' academic performance. However, compared to families with male decision makers, the Chinese scores, math scores, class rank, and grade rank of adolescents from families with female decision makers are higher. This is consistent with the literature suggesting that "compared to men, women usually take greater responsibility for ensuring adolescents' education and thus have a strong preference for educational investment" (Moses, 1977; Xu, 2018; Xinrong et al., 2021; L'Roe et al., 2022). Even under the external risks of land expropriation, women continue to prioritize investment in education.

Table 8 shows the results of the sub-sample regression under the gender difference of adolescents. The analysis reveals that the Chinese and math scores, as well as the class and grade rankings of boys from land-loss families are significantly lower than those of boys from non-land-loss families. The Chinese scores of boys in land-loss families (influence coefficient: −1.1137) are significantly worse compared to the math scores (the influence coefficient is −0.6950). For girls from land-loss families, the Chinese and math scores of the girls are significantly lower than those of girls from non-land-loss families (the influence coefficient was −0.7970), but the class and grade rankings are not significantly different. The regression results also indicate that the coefficient value of the land-loss variable is significantly lower for boys than for girls from land-loss families, which is consistent with the literature that suggests that girls tend to maintain superior academic performance despite adverse learning environments (Hall, 1978; Epstein, 1998; Wei and Chen, 2018). Therefore, it can be concluded that the negative impact of land loss on academic performance is significantly greater for boys than for girls, and is consistent with previous studies (Jiankun and Guangye, 2019). Hypothesis 3 is therefore confirmed.

4.4 Test for robustness

In the above discussion, Chinese and math scores, as well as class and grade rankings of adolescents, were selected as the comprehensive measurement indicators of their academic performance. Table 9 shows the robustness test result, where the total score for Chinese and mathematics was taken as the dependent variable. Fixed-effects and PSM-DID models were implemented to measure the differences in academic

TABLE 9 Robustness test.

Variables	Total score	
	FE	PSM-DID
treated	−1.323**	−1.409**
	(−2.353)	(−2.504)
gender	−1.646***	−1.596***
	(−7.980)	(−7.441)
agep	2.081***	2.099***
	(28.642)	(27.479)
agep2	−0.021***	−0.021***
	(−23.460)	(−22.583)
edumax	−0.156**	−0.231***
	(−2.460)	(−3.180)
fs	0.010***	0.011***
	(4.532)	(4.758)
young	0.352**	0.407***
	(2.334)	(2.583)
old	1.068***	1.0720***
	(7.664)	(7.366)
lnfincome1_per	0.212**	0.453***
	(2.012)	(2.811)
lntotal_asset	−0.341***	−0.345***
	(−3.202)	(−3.058)
fm	−0.324	−0.229
	(−0.881)	(−0.607)
cg	−0.014	−0.008
	(−1.186)	(−0.682)
ch	0.007	0.003
	(0.664)	(0.265)
provcd	−0.234*	−0.295**
	(−1.835)	(−2.216)
Adj. R^2	0.269	0.271

Note: total score = math score + Chinese score; t-value in parentheses; ***$p < 0.01$ **$p < 0.05$ *$p < 0.1$.

performance between adolescents from land-loss and non-land-loss families. The results show that the coefficient value of the land-loss variable is significantly negative. The impact effect (the absolute value of the coefficient) is significantly larger than the impact of Chinese or math scores (the impact coefficients of Models 3 and Model 4 are −0.7352 and −0.6747, respectively). This indicates that adolescents from land-loss families have significantly lower overall performance than those from non-land-loss families and land expropriation will produce a negative intergenerational transmission effect. Therefore, these results confirm that the above regression results are robust.

5 Discussion

The rapid pace of urbanization has led to a significant rise in the number of land-loss farmers. These farmers experience passive urbanization, which forcefully separates them from the traditional agriculture-based rural community, thereby altering their institutional identity (Kumar et al., 2021). Additionally, due to low labor skills, they have an incomplete establishment of the employment relationship network that reflects the modern dimension. Together, the lack of necessary psychological transition and adjustment in the process of urbanization hinders land-loss farmers from adapting to city life. Therefore, it is a realistic problem to consider whether they can integrate into urban life and adjust to urban production immediately after losing their land.

The literature includes a follow-up survey on the income level and life quality of land-loss farmers, revealing that most land-loss farmers experience negative effects during urbanization, such as income decline and a high unemployment rate, which negatively affect the physical and mental development of their children due to changes in their parents' social status (Qin, 2003; Chi, 2004). Adolescence is a critical stage in the formation of individual human capital, and this study focuses on the adolescent group to supplement and verify the relationship between land-loss and adolescent academic performance. The results in Table 3 show a significant negative effect on adolescents' academic performance, confirming that land loss weakens adolescent academic performance and indicating that the negative impact of landlessness on the human capital of family members is intergenerational transmission. This puts the whole family at risk of remaining in chronic poverty, as landless farmers have difficulty entering the higher labor force, and their children lack the ability to access quality educational resources. When farmers' income decreases, they are more likely to prioritize livelihood security over their children's learning and discipline requirements, directing more time and energy toward acquiring employments and constraining their children's learning and educational expenditure, ultimately reflecting a decline in academic performance. This confirms the influencing mechanism of land loss on the academic performance of adolescents based on the logic of "land loss→ family education cognition →family human capital investment→ adolescents' academic performance." Investment in human capital as a mediating mechanism, including both material educational expenditures and immaterial parenting styles, is actually caused by the deterioration of family economic conditions after land loss, and post-loss work status is critical to block or enhance the impact of land loss on children's development (Liu and Xie, 2015; Ma and Lin, 2019). To further alleviate the negative impact of land loss on adolescents' academic performance, vocational training should be strengthened to produce higher marginal benefits and to effectively overcome the unemployment risk.

Previous studies have shown that mothers have a strong preference for educational investments (Wang and Cheng, 2021). Compared to men, women pay more attention to their children's food, clothing, housing, transportation, education, and educational investment, being more motivated to invest in their children's human capital formation (Xinrong et al., 2021). The results of the present study confirm this finding. Children's academic performance is higher in families with female decision makers than in families with male decision makers. Thus, compared to other family members, mothers have a greater influence on children's academic performance, being more inclined to allocate resources toward education.

The boy crisis is a serious issue not limited to China, but observed globally. Boys falling behind in academics will have a significant impact on individuals and society. Moreover, the boy crisis is not limited to academics; boys lag behind in terms of mental health, physical fitness, and social adjustment. This study's conclusion supports the boy crisis theory, specifically shown through the effect of land loss on adolescents' gender. The findings of the current study demonstrate that boys' academic performance is significantly more affected than that of girls, and girls can continue their studies even in an unfavorable learning environment. To promote intergenerational investment in human capital, we should focus on optimizing policies to improve the academic performance of land-loss adolescents and pay more attention to boys. In conclusion, this study will help protect the benefits of land-loss farmers, reduce the risk of unemployment, prevent the adverse impact of land loss on adolescents' human capital investment and academic performance, and help the land-loss group escape poverty.

6 Conclusion and suggestions

In order to identify the impact and mechanism of land loss on the academic performance of rural adolescents, this study utilizes data from the China CFPS 2014 and 2018 and applies the PSM-DID and KHB models to explore the effect and mechanism of land loss on rural family human capital investment and adolescents' academic performance based on the cognition-investment-performance framework. The results indicate that land loss has negative effects on rural families' education expenditure and adolescents' academic performance, verifying the logical mechanism of "land loss→ family education cognition→ family human capital investment→ adolescents' academic performance". Therefore, the following conclusions can be drawn:

The academic performance of adolescents from land-loss families was found to be lower than that of adolescents from non-land-loss families, as measured by class and grade ranking, as well as Chinese and mathematics scores.

Land-loss families were found to have lower awareness of educational value compared to non-land-loss families. As a result, they divert their attention from their children's learning and discipline requirements, leading to lower family spending on children's education.

The logical mechanism of "land loss → family education cognition → family human capital investment → adolescents' academic performance" was verified. The differences in the academic performance of adolescents from land-loss families were found to be jointly affected by educational value cognition, educational resource acquisition scale, and their own learning requirements.

The negative effects of land loss on adolescents' academic performance showed gender differences. The academic performance of adolescents in families with female decision makers was found to be higher than that of adolescents in families with male decision makers, and the academic performance of boys in families with land loss was significantly more affected than that of girls.

Based on the conclusions, we suggest the following policy recommendations:

Improving income provides a good economic foundation for adolescents' education to reduce academic performance loss. This can be achieved through targeted and improved professional training and educational programs for land-loss farmers, as well as differentiated employment and vocational skill training for their diverse needs. An employment information platform for land-loss farmers should be established, and relevant preferential policies should be formulated to guide land-loss farmers in starting businesses and helping them accumulate specific human capital.

The social security system should be strengthened by providing suitable forms of old-age security, expanding the coverage of social insurance, and including land-loss farmers in the urban pension and medical insurance system. The unemployment insurance and assistance system should be improved to ease the pressure of reemployment. Moreover, an educational target management file system for adolescents of land-loss families should be established to ensure they complete school and improve their academic performance.

Employment training and job information for women should be provided to optimize their employment environment. A hierarchical assistance strategy should be implemented to support married and child-bearing women who have lost their land. Family support can be strengthened through sharing more housework and childcare responsibilities and enhancing women's family status. Attention should be paid to the educational needs of boys. Adolescents' mental health education should be strengthened to obtain maximum development opportunities and reduce the impact of land loss on boys' learning status.

This study, however, has some limitations. Although it provides empirical evidence from rural areas in China, it is limited by the use of CFPS survey data. Adolescents' academic performance is obtained by asking parents to evaluate their children's performance, which is subjective and may be biased. Furthermore, while this study provides empirical evidence on the relationship between land acquisition and adolescent academic performance in China, it is unclear whether the findings apply to other countries with different national conditions or resource endowments, particularly in countries with severe land loss conditions. Moreover, in 2021, China introduced a "double reduction policy". Whether the impact of land loss on the human capital accumulation of rural adolescents will change as a result of this policy is a topic worth investigating. Therefore, future research should aim to collect more regional data, describe adolescents' academic performance more objectively, and incorporate real social variables to deepen our understanding of the influence mechanism between the two.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found here: http://www.isss.pku.edu.cn/cfps/.

Author contributions

Conceptualization, JH; methodology, JH; software, JH; validation, JH; formal analysis, JH and RL; investigation, JH; resources, JH; data curation, JH; writing—original draft preparation, JH and RL; writing—review and editing, JH and RL; visualization, JH and RL; supervision, JH and RL. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by the National Social Science Foundation of China, "Research on Intergenerational Conflict and Intervention Countermeasures of Rural Family Parenting Support;" Ningxia Natural Science Foundation Project "Decision-making Mechanism and Simulation of Rural Family Human Capital Investment Based on ABM;" Ningxia University first-class discipline construction (theoretical economics) funding project, grant numbers 21CSH020, 2022AAC03015, and NXYLXK 2017B04.

Acknowledgments

We thank commentators and editors.

Conflict of interest

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 07 July 2023
DOI 10.3389/fenvs.2023.1214372

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OPEN ACCESS

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RECEIVED 29 April 2023
ACCEPTED 20 June 2023
PUBLISHED 07 July 2023

CITATION
Li Q, Ai F, Kang F, Zhang Z and Tuo D (2023), Construction and application of a new index for root architecture quantification in arid and semi-arid regions.
Front. Environ. Sci. 11:1214372.
doi: 10.3389/fenvs.2023.1214372

Construction and application of a new index for root architecture quantification in arid and semi-arid regions

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During the restoration of degraded vegetation, the mutual matching of underground root systems is crucial for the formation and effective function of the future plant community. In this study, the Amoeba graphic method was integrated to comprehensively establish a root framework index (RFI), based on the three dimensions of root morphology, as well as quantitative and spatial connection characteristics, to quantify the root system architecture. The root development characteristics of alfalfa (T-type), switchgrass (F-type), and mixed planting with alfalfa and switchgrass (T+F-type) were monitored at the test positions. The RFI parameters comprise the acting coefficient of the root framework, root density, root framework degree, and soil bulk density. The RFI values of T-, F-, and T + F-type were 0.38, 0.86, and 1.68, respectively, and were found to provide a well representation of the root structure characteristics. The findings obtained in this study provide scientific support for the ecological construction and evaluation of degraded vegetation.

KEYWORDS

root density, root framework degree, root framework index, root structure, degraded vegetation

1 Introduction

Plant roots and soil form a root–soil complex system through network connections, root–soil binding, and biochemical processes, which are highly important for the effective restoration of degraded vegetation and ecological sustainability (Yen, 1987; Li et al., 2017). During the construction of vegetation under unfavorable habitats affected by stress, such as drought, the root system can adapt and maintain the stability of the plant community through bending and winding, decreasing the branching capacity, increasing the connection length, and adjusting the turnover time, thereby allowing for adaptation to a wide range of ecological conditions (Doussan et al., 2003; De Baets et al., 2008; Huang et al., 2019). Therefore, mutual matching of the underground root system during the restoration of degraded vegetation will be key to the formation and effective functioning of plant communities with a well structure in the future (Wang et al., 2019a; Wang et al., 2019b).

For a single vegetation type, the root architecture, i.e., the interconnection and spatial distribution of roots at different levels in the same plant root system, is an important indicator of the root system structure (Guo et al., 2019). Previous studies on root architecture characteristics have focused on quantitative indicators, such as root density (Rd), root length density, effective Rd, and root specific surface area density, as well as other spatial indicators, including the root topology index, connection length, and branching rate (Li et al., 2016a; 2016b; Yang et al., 2018). The characteristics of the horizontal distribution of the uniform root system and the root system bending characteristics have been integrated to describe root system morphology and distribution (Nicoll et al., 2006; Wang et al., 2020). In an innovative approach for quantifying root systems, the Amoeba graphical method has been used in some studies to quantify the overall root system configuration by using three indicators: root diameter, root depth, and root length (Zhang et al., 2016). However, in reconstruction of the vegetation modes of two or more plant species, the root systems of different plants may form a rigid framework with the soil through branching connections, and thus the root architecture concept may not be suitable for representing these structural features and functions. Therefore, it is extremely important to comprehensively characterize root structural traits and develop a quantifiable root framework index (RFI) by effectively integrating root morphological features, quantitative characteristics, and spatial connections (Li et al., 2020a; Li et al., 2020b).

Based on three principles, including scientific credibility, effectiveness, and practicality, in this study, we selected key indicators for describing the root structure according to the dimensions of plant root morphology, quantitative features, and characteristic spatial connections. We used the Amoeba graphic method to establish an RFI for typical plant reconstruction models in loess hilly areas, thereby providing scientific support for the ecological construction and evaluation of degraded vegetation.

2 Materials and methods

2.1 Study area

The study area is located at the Ansai Water and Soil Conservation Comprehensive Experimental Station of the Chinese Academy of Sciences, China (109°19′ 23″E, 36°51′30″N). The annual average rainfall in this area is 505.3 mm, but the inter-annual variation is high, and the distribution is uneven throughout the year. More than 60% of the precipitation is concentrated between July and September. The soil in this area is loessal and silt–loamy, with a clay, silt, and sand content of 9.3%, 57.4%, and 33.3%, respectively. The soil organic matter content is 3.65 g kg^{-1}, and the pH is 8.56.

2.2 Experimental design

The study area had long been used for growing potatoes, millet, and other crops before 2001. The plot was abandoned between 2001 and 2009. In May 2009, the area was reclaimed as agricultural land for growing potatoes, millet, and other crops in three consecutive years (2009–2012). The trial was conducted in mid-May 2012. The experimental treatments involved growing the following plants and combinations: (1) alfalfa (*Medicago sativa*) with a typical taproot (T) system (251 plants m^{-2}), (2) switchgrass (*Panicum virgatum*) with a typical fibrous (F) root system (157 plants m^{-2}), and (3) mixed sowing of alfalfa and switchgrass (T + F). Each treatment plot had an area of 27 m^2 (9 m × 3 m), with a slope of 20° to the northeast. The topsoil was artificially loosened, and large soil particles were broken into soil particles <1 cm in diameter. No treatments were fertilized before sowing. Because of the small size of the seeds, random sowing per unit area (m^2) was conducted after sowing with dry soil of the same quality, to avoid an influence of sowing direction (Li et al., 2015).

2.3 Statistical analysis

Analyses of the acting coefficient of the root framework, root density (Rd), root framework degree (S), and root framework index (RFI) were performed in Microsoft Office 2019. The graphs were generated in SigmaPlot 18.0. The significance of differences was tested with the least significant difference method ($p < 0.05$).

3 Results

3.1 Construction of the RFI

The root framework should comprehensively characterize the root structure characteristics in terms of the morphological, quantitative, and spatial characteristics of the root system. The four assumptions of the root framework are: (1) the existence of two or more morphological root systems, (2) a certain root biomass, (3) a fine root spatial structure, and (4) specific soil structure properties. In this study, we selected four indicators, including the coefficient of root framework, root density, root framework degree, and soil bulk density—based on our field research and practice, as well as the principles of scientific credibility, effectiveness, and practicability.

1) Acting coefficient of the root framework. Various forms of plant roots differ in terms of their branch connections, root–soil binding, and biochemical effects in the soil. In this study, the acting coefficient of the RFI, i.e., the slope of the linear relationship between the root system mass density and the planting time, was used to characterize the root morphology.
2) Root density. This indicator was to describe the quantitative characteristics of the RFI. The root biomass was obtained by repeatedly washing the roots in a sieve before oven drying at 80 °C to a constant weight. Rd is calculated as follows:

$$Rd = M/V \tag{1}$$

where Rd is the root density (kg m^{-3}), M is the mass of the dried root system (kg), and V is the sample volume (m^3).

3) Root framework degree. Based on a previous study (Zhang et al., 2016) and the principles of scientific credibility, effectiveness, and practicability, we selected three indexes—root diameter (X), root length (Y), and root depth (Z)—to establish a three-dimensional coordinate system. The volume formed in

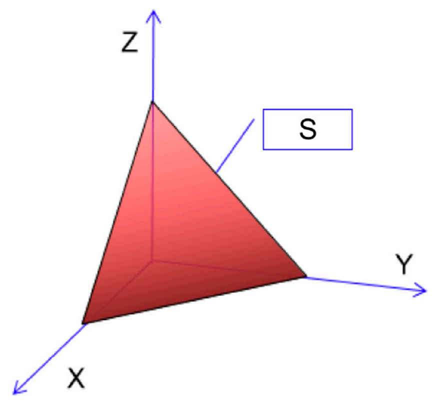

FIGURE 1
Schematic diagram of Amoeba. S, root framework degree; X, root diameter; Y, root length; Z, root depth.

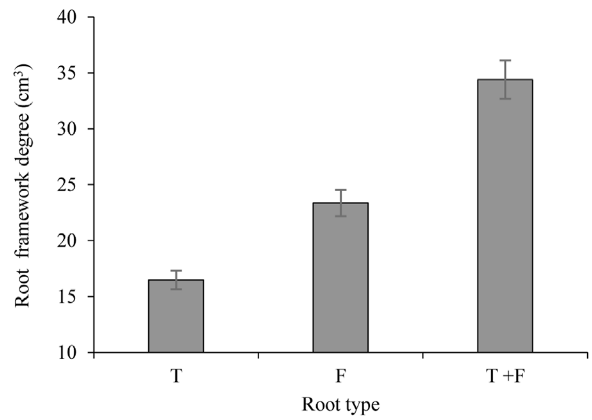

FIGURE 3
Root framework degree in different root types.

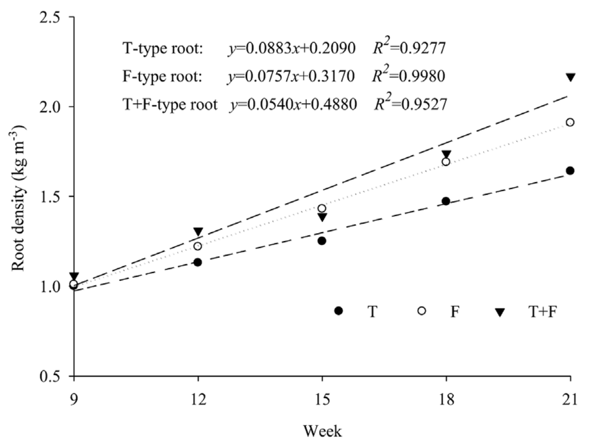

FIGURE 2
Root density in different root types during the growth.

Amoeba by connecting the three points was set as the root framework degree and was used to characterize the spatial connection characteristics of the RFI (Figure 1). The root framework degree was calculated with the Amoeba graphical method; therefore, the indicator had mathematical meaning but no physical meaning and thus was regarded as dimensionless. The root framework degree is calculated as follows:

$$S = \frac{1}{6}abh \tag{2}$$

where S is the root framework degree, a is the average root diameter (cm), b is the total root length (cm), and h is the maximum root depth (cm).

4) Soil bulk density. According to the principles of scientific credibility, representativeness, and accessibility, the soil bulk density was selected to indicate the soil structural properties by using following Equation:

$$\rho = m/v \tag{3}$$

where ρ is the soil bulk density (g cm^{-3}), m is the mass of dried soil (g), and v is the volume of the soil sampler (100 cm^3).

Finally, the root framework index (RFI,%) can be calculated from the following equation:

$$RFI = \frac{\alpha \times R_d \times S}{\rho} \times 100\% \tag{4}$$

3.2 Application of RFI

3.2.1 Acting coefficient of the root framework

Figure 2 shows that the Rd values for T-type, F-type, and T + F type planting increased in a linear function with the planting age, and the coefficients of determination for the linear regression models all exceeded 0.94. The slope indicators suggested that the acting coefficients for T-, F-, and T + F-type roots were 0.162, 0.227, and 0.265, respectively. These results showed that the root biomass growth rate in mixed T + F plants was greater than that in T- or F-type plants. Moreover, the T + F-type plant combination formed a stable root framework more readily than the T- or F-type treatment.

3.2.2 Root framework degree

The root framework degree refers to the three-dimensional structure of plant roots in the soil, which reflects the spatial framework of the roots. Figure 3 shows that the root framework degree for the T-, F-, and T + F-type roots was 16.48, 23.32, and 34.40, respectively. The root framework degree for F-type roots was 6.84 higher than that for T-type roots, representing an increase of 41.5%. The root framework value for T + F-type roots was 17.92 and 11.08 greater than that for T- and F-type roots, respectively, representing increases of 108.7% and 50.6%, respectively.

3.2.3 RFI

RFI is a parameter used to comprehensively quantify plant root structure in three dimensions according to the root morphology,

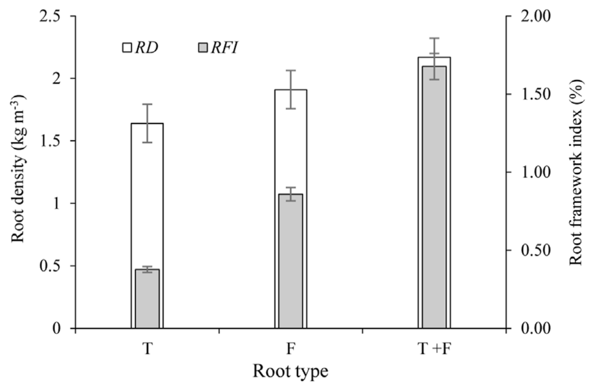

FIGURE 4
Root density and root framework index in different root types.

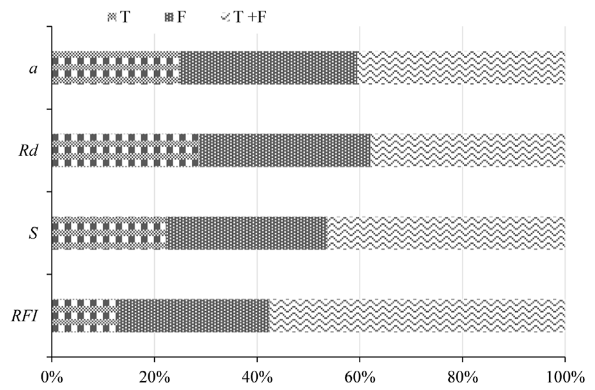

FIGURE 5
Relative contribution of root architecture on *a*, *Rd*, *S*, and *RFI*.

root coefficient, and root spatial connection characteristics. As shown in Figure 4, the RFI values for T-, F-, and T + F-type plants were 0.387, 0.851, and 1.676, respectively. The RFI value for F-type plants was 0.464 higher than that for the T-type root system. The RFI value for T + F type plants was 1.289 and 0.825 higher than that for T- and F-type roots, respectively, representing increases of 3.3-fold and 0.97-fold. These differences were similar to the changes in Rd. However, the root system spatial connection characteristics were probably incorporated into the RFI, thereby increasing the differences between the treatments. Therefore, the RFI values obtained for T-, F-, and T + F- type plants effectively reflected the characteristics of the root system structures.

4 Discussion

The root density, root specific surface area density, fractal dimension, connection length, and topological structure, as well as other parameters, have been widely used for describing root systems. Some studies have used Rd to evaluate the restoration effect of degraded grassland and have determined an effective density, denoted the optimal root content (Tang et al., 2016; Bo et al., 2019).

Figure 5 shows that the optimal root content may change if the root spatial connection characteristics are considered. The growth characteristics of the root systems in different plant species can vary in terms of the framework level and stability (Niu et al., 2019). RFI was applied to the root–soil complex system formed by two or more plant roots in the soil through branch connections, root–soil binding, and biochemical interactions (Fan et al., 2010). The RFI constructed in this study comprehensively quantifies and characterizes the root structure characteristics based on the dimensions of root morphology, quantitative features, and space; moreover, it objectively reflects the effects of the mutual matching of different root morphologies, and it accurately represents the anchoring effect of deep roots and the reinforcement effect of shallow roots. Moreover, because obtaining the required indicators is simple, the RFI should support studies on the structure of plant roots and the evaluation of plant community ecological construction (Yang et al., 2011).

During the development of vegetation in unfavorable habitats, such as those affected by drought, roots can adapt and maintain the stability of the plant community by bending and winding, decreasing the branching capacity, increasing the connection length, and adjusting the turnover time, thereby allowing for adaptation to a wide range of ecological conditions. When plants are affected by wind, their underground root systems bend. Most of the root mass is distributed in the downwind direction when plants grow on flat ground, whereas more of the root mass is distributed in the upwind direction when root systems grow on sloping ground. Therefore, future studies using the RFI should comprehensively consider the relationships among soil structure, species attributes, and the external environment, and should weight the parameters in the model to evaluate the stability and sustainability of plant communities on a larger scale (Lifschitz et al., 2022). The RFI constructed from the perspective of mutual matching of underground root systems is helpful for evaluating vegetation restoration effects, and it may support evaluations of regional ecosystem services (Zhu et al., 2019).

5 Conclusion

In this study, based on the root growth characteristics of T-type, F-type, and T + F type plants in a loess hilly area, we established the RFI according to three dimensions: root morphology, functional coefficient, and root spatial connection characteristics. The parameters of the RFI comprise the acting coefficient of the root framework, R_d, root framework degree, and soil bulk density. We determined the RFI values for T-, F-, and T + F-type plants to be 0.38, 0.86, and 1.68, respectively. RFI could effectively reflects the root structure characteristics of vegetation and provides scientific support for ecological construction processes and evaluation of degraded vegetation.

Data availability statement

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

Author contributions

Conceptualization, QL and DT; methodology, FA and FK; investigation, ZZ and DT; data curation, ZZ; writing—original draft preparation, QL; writing—review and editing, QL and DT; supervision, QL and DT. All authors contributed to the article and approved the submitted version.

Funding

Financial assistance for this study was provided by the projects of the National Natural Science Foundation of China (Grant No. 42207412, 42267071, 41907059), National Key Research and Development Program of China (2022YFF1300802).

Acknowledgments

We also express our gratitude to the reviewers and editors for their constructive comments and suggestions.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 21 August 2023
DOI 10.3389/fenvs.2023.1115640

Regulation and optimization of cultivated land in different ecological function areas under the guidance of food security goals-a case study of Mengjin County, Henan Province, China

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RECEIVED 04 December 2022
ACCEPTED 03 August 2023
PUBLISHED 21 August 2023

CITATION
Guan X, Wang X, Zhang J and Dai Z (2023), Regulation and optimization of cultivated land in different ecological function areas under the guidance of food security goals-a case study of Mengjin County, Henan Province, China. *Front. Environ. Sci.* 11:1115640.
doi: 10.3389/fenvs.2023.1115640

China's arable land is facing the dual constraints of increasing "non-grain" and tightening ecological control. However, extreme emphasis on food production or excessive attention to ecological protection cannot effectively solve the practical problems of cultivated land utilization. In this paper, evaluation indexes were selected from the aspects of ecological service, landscape integrity, ecological sensitivity, etc., and ecological importance evaluation system for territory space was constructed. The ecological importance of territorial space was divided into three ecological functional areas, namely, the extremely important regions, the relatively important regions and the general regions. The morphological characteristics of cultivated land use in different ecological function areas were described systematically, and the main problems of cultivated land use in different regions were analyzed. On the basis of ensuring the ecological security of territorial space, this paper puts forward the regulation and control plan of cultivated land in different ecological functional areas aiming at food security, and makes an empirical study with Mengjin County as the case area. The results showed that: under the guidance of food security objectives, the implementation of different types of cultivated land remediation programs according to the problems existing in different ecological functional areas could guarantee food security to the greatest extent and amplify the ecological and environmental effects of land remediation. By means of land consolidation and ownership adjustment, the abandoned farmland in general and relatively important ecological regions can be restored for food use, which can not only enhance the food supply capacity, but also without causing damage to the ecological environment. There is a large area of arable land in the ecologically extremely important regions. Large-scale ecological conversion will have a certain impact on food security supply. Promoting ecological farming is an important way to resolve the contradiction between food safety production and ecological environment protection. This study can provide reference for decision making of arable land consolidation in the new period.

KEYWORDS

cultivated land, food security, ecological security, regulation, Mengjin

1 Introduction

Food security is an overarching and strategic issue concerning national development. In China, where human-land conflicts are relatively tense, maintaining the stability of cultivated land areas does not only guarantee food supply but is also the basic condition for realizing economic development, social stability and ecological security. Influenced by the COVID-19 pandemic and the Russia-Ukraine war, many countries have adopted restrictions or bans on food exports. As the alarm bell of the food crisis sounded, issues related to farmland protection and food security have re-escalated (Kong, 2020; Wang and Hou, 2021).

The safe use of cultivated land resources is the basic resource to ensure food security and the landscape matrix to maintain ecological security (Guo et al., 2015; Sun et al., 2020; Ye et al., 2020; Liu et al., 2021). In view of the practical trade-offs between the rigid management and control of cultivated land protection and the mismatch with regional resource spaces in this new era, experts of cultivated land protection have carried out key studies on the quality of cultivated land (Kong et al., 2018; Wen et al., 2019a; Feng et al., 2019; LV et al., 2020), healthy productivity (Gao et al., 2018; Wen et al., 2019b; Zhang et al., 2020), risk management and control (Tang et al., 2020; Zhao et al., 2020; Guan et al., 2020; Wei et al., 2021) and other fields. Relevant studies have provided beneficial information for developing a healthy agricultural system in the new era and supporting a healthy China.

China attaches great importance to cultivated land protection and has built a relatively perfect cultivated land protection system (Liu et al., 2020; Lu et al., 2021; Zhou et al., 2021). However, with the optimization and upgrading of the agricultural industrial structure and the continuous migration of the rural labor force to cities and towns, the trend of "non-grain" cultivation characterized by a decline in production has become increasingly intense (Yang and Zhang, 2021; Su et al., 2020; Guan et al., 2021; Guan et al., 2022). The essence of farmland "non-grain" is the adjustment of agricultural production structure. The main body of cultivated land management makes decisions on agricultural production and planting type under the influence of many factors such as cost-income benefit, natural resource endowment, national policy orientation and family characteristics (Sun et al. ,2020; Wei et al., 2023; Cheng et al., 2023). As "non-grain" cultivation is affected by multiple factors, such as market demand, management policies, farmers' decisions and land conditions, it is necessary to take comprehensive measures to effectively resolve this problem. If the continuous development of "non-grain" cultivated land is allowed, it will certainly threaten the security of China's cultivated land resources, the absolute security of national grain resources, and the natural ecological security of cultivated land. With the increasing attention of the state to ecological protection, most ecological functional areas are listed as the ecological red line. The construction of a good biological habitat environment and the struggle for more ecological space for nature will inevitably lead to the intensified conflict between agricultural space and ecological space. However, extreme emphasis on grain production or excessive attention to ecological protection cannot effectively solve the practical problems of cultivated land utilization. Therefore, on the basis of ensuring ecological security, it is of great significance to promote the resumption of grain production of cultivated land through effective control and management of "non-grain cultivated land" to maintain food security.

Traditional agricultural utilization mainly emphasizes the productive function of cultivated land. With the continuous development of modern agriculture, the human demand for cultivated land is different and changes in stages. The function of cultivated land is increasingly showing the characteristics of diversity, and the leisure and entertainment function of cultivated land is receiving increasing. At present, the multiple functions of cultivated land have been widely studied by researchers at home and abroad, and related research has gradually increased. These studies mainly include the concept and characteristics (Blum et al., 2006; Vander et al., 2009; Song and Ou., 2012; Coyle et al., 2016), research methods (Jiang et al., 2011; Li et al., 2017; Xin et al., 2017; Wang et al., 2018) and evolution of multi-functional cultivated lands (Wilson, 2008; Song and Liu, 2011; Yang and Tan., 2014; Shi et al., 2015). Compared with other land types, the food production function of cultivated land is irreplaceable by other land types. At the same time, the ecological and landscape cultural functions of cultivated land have much room for improvement and can replace other land functions to a certain extent (Zasada, 2011; Liu et al., 2018; Yang et al., 2022). Although with the economic and social development and the adjustment of national strategy, the academic circle's attention to the function of cultivated land is constantly changing, the core issue is always around production function, living function and ecological function (Qian et al., 2020; Xiong, 2021; Zou et al., 2021). It is very important to effectively measure various functional values of cultivated land. However, there is no unified understanding on which indicators are scientifically standardized for the multifunctional evaluation of cultivated land, and unscientific functional division and indicator selection will affect the evaluation results (Zhang et al., 2018; Wang et al., 2022). For example, the use of chemical fertilizers and pesticides will change the production function of cultivated land, but also change the ecological function of cultivated land, which easily leads to the selection of different indicators will evaluate the different results.

China has a large population and little land, and cultivated land resources are extremely scarce. Only by giving full play to the multifunction of cultivated land resources can we meet the actual needs of national food security and ecological security. Based on this situation, this study established the ecological importance evaluation system of territory space, divided the ecological function zones of territorial space, identified the rigid bottom line of maintaining regional ecological security, systematically described the morphological characteristics of cultivated land use in different ecological functional regions, diagnosed the main problems existing in the utilization of cultivated land in different ecological functional regions. On the basis of ensuring ecological security, the multi-function of cultivated land utilization was given full play, and the direction of cultivated land consolidation and regulation in different ecological functional regions was proposed, in order to achieve the "double best" goal of food security and ecological improvement.

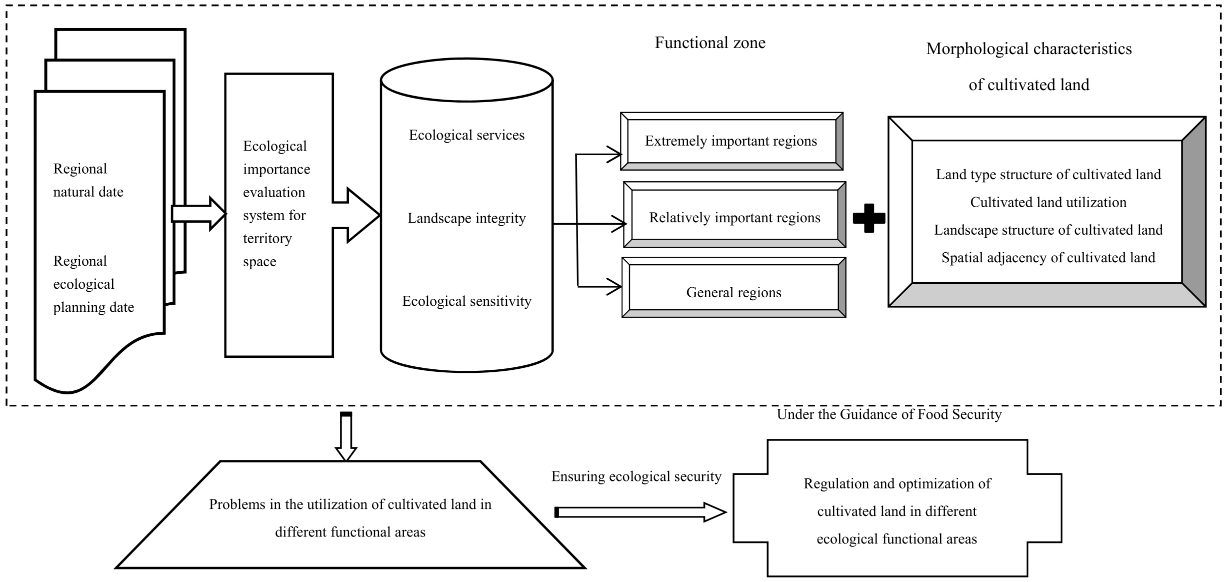

FIGURE 1
Framework of cultivated land consolidation in different ecological functional regions.

2 Theoretical framework

2.1 Regulation framework of cultivated land in different ecological functional regions

Firstly, according to the regional natural and ecological planning data, the ecological importance evaluation index system of territorial space was constructed from the aspects of ecological service, landscape integrity and ecological sensitivity, and the ecological function range of territorial space was identified. Secondly, the land structure, utilization status, landscape structure and spatial adjacency characteristics of cultivated land in different ecological functional areas were identified by overlaying the status of cultivated land utilization with the evaluation results of the ecological importance of territorial space, and the main problems in the utilization of cultivated land in different ecological functional areas were diagnosed. Finally, with the aim of food security supply and on the basis of ensuring ecological security, we put forward the path of arable land consolidation and optimization regulation in different ecological functional regions (Figure 1).

2.2 Ecological importance assessment of territorial space

Ecological importance assessment of territorial space is the process of dividing regions into spatial units with different ecological functions based on the characteristics of regional ecosystems and the sensitivity of the ecological environment. This process involves systematically referring to existing research results on territorial space ecological security evaluations (Yu et al., 2009; Xie and Li, 2011; Guan et al., 2013; Guan et al., 2017; Fu, 2019), is based on the cognition of land ecosystem attributes, emphasizes the long-term stability of territorial space ecological security, gives full consideration to the representativeness of the indicators and the accessibility of the data by closely comparing them against the actual situation of the research area. Evaluation factors were selected from the aspects of ecological services, landscape integrity and ecological sensitivity, and an evaluation index system of territorial space ecological importance was scientifically constructed (Table 1).

(1) Ecological services

Land use pattern changes affect ecological processes, which in turn affect ecosystem services that couple natural and social systems (Fu, 2019). The ecological importance of territorial space is closely related to the type of land use. The actual situation of the region is accurately understood, and water resource factors are regarded as the most rigid evaluation indices. The ecosystem service function of national space is related to plot area. The larger the area of a certain land use type is, the richer its biodiversity is and the stronger its anti-interference ability is. The smaller the plot area is, the weaker its ecological function is. Wetlands are known as the kidneys of the Earth. The published wetland conservation plan divides wetlands into core areas, pilot areas and buffer zones, and the evaluation score of the wetland reserve is determined according to the protection plan. The ecological red line plays a key role in maintaining the stability of the natural ecosystem and ensuring regional ecological security. Therefore, the land within the ecological red line is directly included as an extremely important area.

(2) Landscape integrity

The stability of the regional ecological structure and function can be realized only by maintaining the integrity of the ecosystem. Landscape integrity is an important indicator of territorial space ecological security. The mountains, water and wetlands constitute the main body of regional seed patches, which play an important

TABLE 1 Ecological importance evaluation system for territory space.

System layer	Index layer	Factor grade and score					Weight
		5	4	3	2	1	
Ecological services	Land use types	Tidal flats/ waters	Woodland/ garden	cultivated land	Unused land/other agricultural land	Construction land	0.156
	Land area/hm^2	>20	15–20	10–15	5–10	<5	0.115
	Wetland reserve	core region	Test area	buffer area		Other areas	0.219
	Ecological red lines	Directly into the very important area					
Landscape integrity	Distance from the Seed patch/m	<1,000	1,000–2000	2000–3,000	3,000–4,000	>4,000	0.132
	Distance from the river/m	<500	500–1,000	1,000–1,500	1,500–2000	>2000	0.112
Ecological sensitivity	slope/(°)	>25	15–25	8–15	5–8	<5	0.146
	Soil texture	silty	Sandy loam	loam	Loamy clay	Clay loam	0.120

role in maintaining the stability of the regional ecological structure. Rivers, as natural linear ecological structure elements, can effectively connect ecological patches to maintain the continuity of natural landscapes. Using GIS, regional seed patches and rivers are spatially buffered, and spatial values are assigned according to buffer distance to evaluate the integrity of the regional landscape structure.

(3) Ecological sensitivity

Ecological sensitivity refers to the degree of response of regional ecosystems to human disturbance and natural environmental changes. As the habitat of many microbial resources, soil itself has a buffering and filtering function. The more fragile the soil ecological environment is, the stronger the regional ecological sensitivity is. Based on an overall understanding of the regional natural situation and with reference to relevant studies (Xie and Li, 2011; Guan et al., 2013), the soil texture and topographic slope are combined to evaluate the regional ecological sensitivity.

Per the advice of multiple experts, the land parcel was determined to be a proper evaluation unit for index assignment and the analytic hierarchy process was used to determine the weight of the evaluation index (Table 1), and the ecological importance index of each land parcel was calculated through the comprehensive weighting model using the following formula:

$$Z = \sum_{k=1}^{n} G_k \times W_k$$

Z: Ecological importance index of the evaluation unit;
n: Number of evaluation factors;
G_k: Quantization score of the kth evaluation factor;
W_k: The weight of the kth evaluation factor.

2.3 Landscape pattern analysis

The landscape pattern index of cultivated land is highly concentrated information of the spatial pattern of cultivated land, which can effectively reflect the structural composition and spatial morphological characteristics of cultivated land resources (Guan et al., 2013; Guan et al., 2017). After 10 m*10 m rasterization, the landscape pattern characteristics of cultivated land under different utilization modes were calculated using the landscape pattern analysis software Fragstats 4.2.

2.4 Spatial adjacency analysis

The function and structure of patches are closely related to their spatially adjacent patch types (Fu, 2019). By analyzing the characteristics of their spatially adjacent patches, the potential risks on the utilization form of target patches or the degree of influence of the surrounding land types can be effectively diagnosed. The characteristics of spatially adjacent cultivated land patches can be obtained by buffering and superposition cultivated land patches and global map patches.

3 Material and methods

3.1 Study area

Mengjin County is located in midwestern Henan Province at the geographical boundary of the middle and lower reaches of the Yellow River. Mangshan Mountain is a remnant of the Loess Plateau in midwestern Mengjin County, and the Yellow River terrace in the northeast is relatively flat (Figure 2). The highest altitude in the western mountain area is 471 m, and the lowest altitude on the eastern Yellow River beach is 120 m, which is 55.5 km long from east to west and 26.9 km wide from north to south, with a total area of 734.77 km^2.

The Yellow River enters Mengjin from Xin'an County in the west and flows through the towns of Xiaolangdi, Baihe and Huimeng. Xiaolangdi Dam is located in the village of Xiaolangdi. The Xiaolangdi Reservoir covers a total area of 272 km^2. The Xixiayuan Reservoir dam is located in the village of Xixiayuan. The Xixiayuan Reservoir is relatively open, with a total storage capacity of 145 million m^3 and an average water depth of 4–6 m.

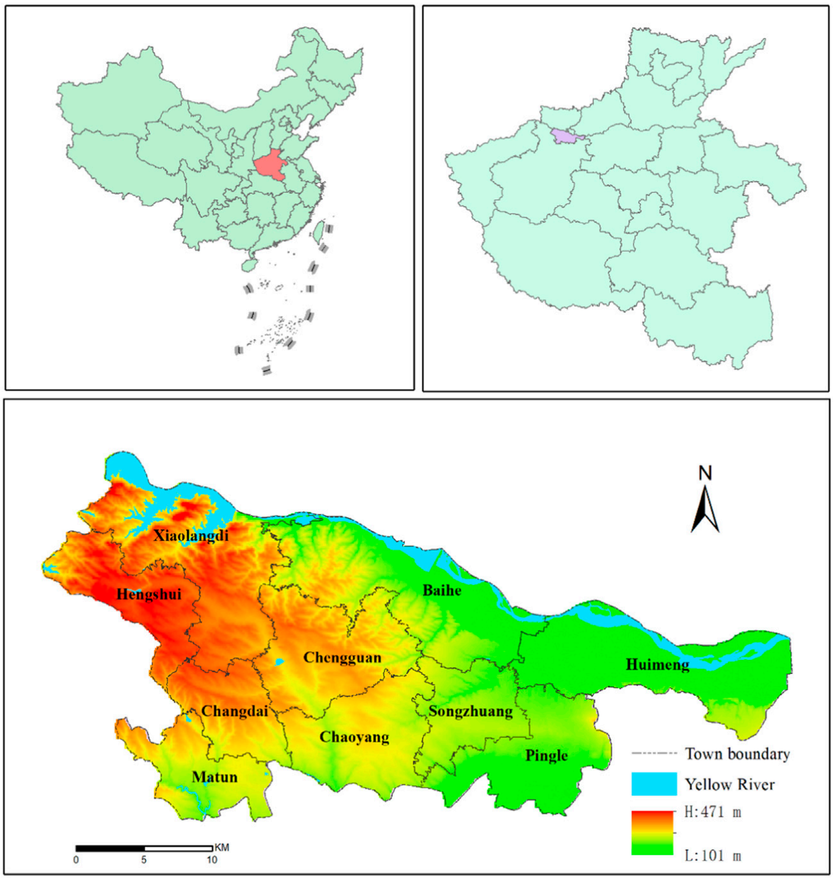

FIGURE 2
Location of the study area and the DEM of Mengjin Contry.

Mengjin County, as a typical county in the middle and lower reaches of the Yellow River, has a special geographical environment. Located in the northern part of the county are the Xiaolangdi Reservoir, Xixiayuan Reservoir and Yellow River channel. Since the operation of the Xiaolangdi Water Conservancy Project in July 2000, the main channel of the Yellow River has been controlled within a fixed channel, and the coastal tidal flat in the northeast of the county has changed from seasonal flooding to large-scale agricultural development, resulting in a continuous shrinkage of tidal flat wetlands. The influence of cultivated land development and utilization on regional ecological security was ignored. In the northwest is the loess gully region along the Xiaolangdi Reservoir, which is characterized by a steep topography, high field fragmentation, high ecological sensitivity and inconvenient farming. With the gradual attrition of the agricultural labor force, farming is frequently abandoned. The southern part of the county is adjacent to the urban area of Luoyang, and under the influence of urban expansion, high-quality agricultural space is constantly replaced by construction, which has creating some underlying concerns for food security production.

3.2 Data sources

The land use data were obtained from three land survey databases provided by the Natural Resources Bureau of Mengjin County. Data on the ecological red line were obtained from the Natural Resources Bureau of Mengjin County. The water source and wetland protection regionalization data were from the Master Plan of Henan Yellow River Wetland National Nature Reserve (2012–2020). Digital Elevation Model (DEM) data and soil data were obtained from the Data Center of the Chinese Academy of Sciences (http://www.resdu.cn).

In terms of data processing, ArcGIS 10.2 was used to carry out unified spatial coordinate registration of the relevant vector data and to obtain basic data on the ecological importance evaluation of territorial space by spatial buffering of relevant evaluation indicators. Combined with the research needs, realistic characteristics of regional land use, and land use classification according to national spatial planning, land use data from 7 categories were included in the study area, including cultivated land (paddy fields, irrigated land, dry land), garden land (orchard, and other garden), forestland (arbor forestland, shrub land, other forestland), grassland (artificial grassland and other grass), other agricultural land (breeding pits, facilities, agricultural land, rural roads, pits or water), construction land (rural housing land, town/village roads, public facility land, science, education, culture and health land, special land, highway land, etc.), and unused land (river water surface, lake water surface, idle land, bare land, bare rock and gravel land, inland tidal flat, reservoir water surface), and a 10 m × 10 m rasterization treatment was performed.

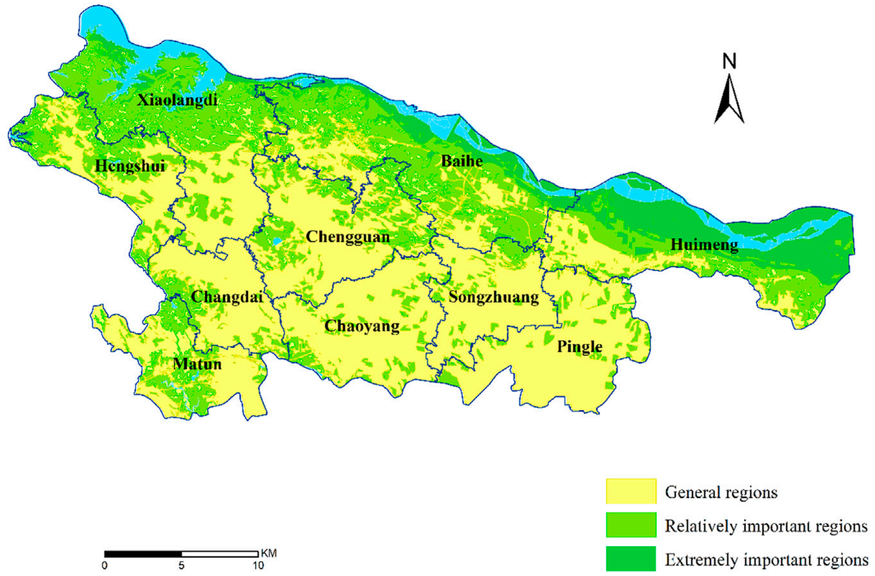

FIGURE 3
Spatial distribution of ecological importance within Mengjin County.

4 Results

4.1 Evaluation of the ecological importance of territorial space

The ecological importance of territorial space is reflected by the ecological importance index of territorial space. The higher the index is, the greater the ecological importance. The spatial ecological importance index of Mengjin County ranges from 1 to 4.333, and the natural fracture point method is adopted to divide the regional territorial space into extremely important regions (2.908–4.333), relatively important regions (2.001–2.908) and general regions (1–2.001).

4.1.1 Extremely important regions

As shown in Figure 3, the extremely important areas are mainly distributed in the Yellow River Valley along the Yellow River at the northern edge of Huimeng, Baihe and Xiaolangdi, with an area of 104.61 km^2, accounting for approximately 14.24% of the county's land area. The area belongs to the long and narrow valley terrace, there is a relatively flat terrain in the area, and the Yellow River serves as a very large ecological corridor. The Xiaolangdi Reservoir, Xixiayuan Reservoir, and the Yellow River wetland reserve effectively maintain the stability of the ecological structure, the regional landscape integrity is strong, the area is rich in biodiversity, the Yellow River Basin area maintains the water ecological security, and the area has an extremely important level of ecological importance.

4.1.2 Relatively important regions

The relatively important areas are mainly distributed in southern Xiaolangdi, southern Baihe, southern Huimeng and western Hengshui on the periphery of the very important areas and are somewhat distributed in the towns of Changdai and Matun, with an area of 245.26 km^2, accounting for 33.37% of the total land area. This region is a typical loess gully region with fragmented plots and a strong ecological sensitivity. Improper agricultural use easily causes soil and water loss. The land use in this region is based on forestland and cultivated land, and there are construction land patches with poor landscape integrity.

4.1.3 General regions

The general regions are mainly distributed in the towns of Chengguan, Chaoyang, Songzhuang and Pingle, with an area of 384.90 km^2, accounting for approximately 52.38% of the county's land area. These general regions make up the main body of Mengjin County's land space. This area mostly has a gentle, hilly slope because the seasonal flow of the Chan River through the area leads to a lack of large habitat patches, the area of cultivated land and construction land being more mixed, landscape patches, a weak overall regional ecological service function, and a general level of ecological importance at the national scale.

4.2 Morphological characteristics of cultivated land use in different ecological function zones

4.2.1 Land type structure of cultivated land in different ecological function zones

The total cultivated land of Mengjin County is 29987.42 h m^2, among which the paddy field area is 971.13 h m^2, accounting for approximately 3.24% of the total cultivated land, which is mainly distributed along the Yellow River beach of the town of Huiming. The irrigated land area is 10166.5 h m^2, accounting for 33.90% of the total cultivated land area, mainly distributed in Huimeng, Songzhuang, Chaoyang, Pingle and other towns. The dry land area is 18849.79 h m^2, accounting for 62.86% of the total

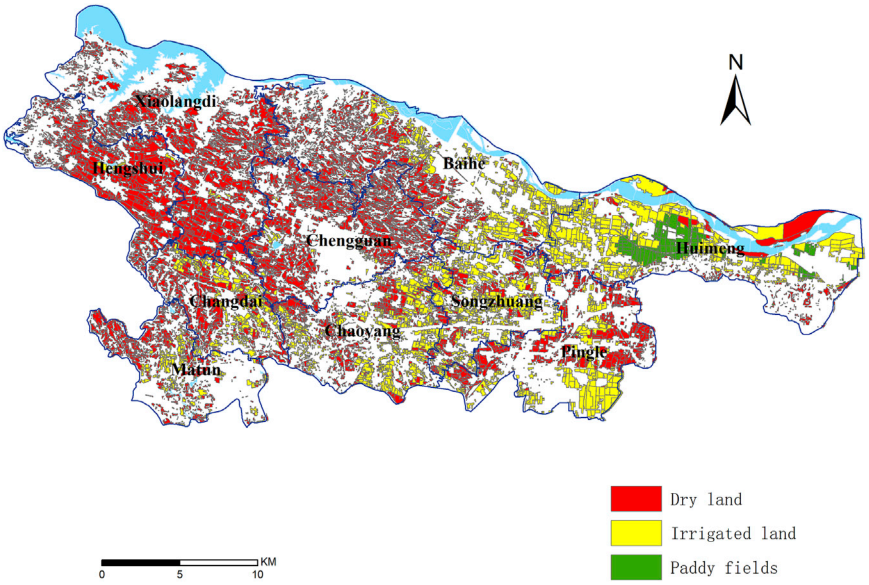

FIGURE 4
Spatial distribution of cultivated land use types in Mengjin County.

cultivated land area, mainly within Xiaolangdi, Hengshui, Changdai, Chengguan and other townships. The quality of cultivated land in Mengjin County as a whole is not high, and its distribution is shown in Figure 4.

Because of the extremely important region near the Yellow River and the importance of the land along the river, the water resource conditions are relatively superior, with an ecologically extremely important paddy field area of 548.60 h m^2, representing approximately 56.49% of the county's area of paddy fields. Under the condition of limited water resources, rice cultivation has utilized a large amount of the region's natural water source, which is also an important reason for the shrinkage of wetlands in the Yellow River beach area.

The relatively important region is on the outer area of the ecologically extremely important area, and its water resource condition is second only to the extremely important area. The paddy field area is 404.43 h m^2, accounting for 41.64% of the paddy field area in the county. However, restricted by topographic conditions, the area of dry land in this region is 8363.96 h m^2, accounting for approximately 73.01% of the area of cultivated land in ecologically important areas, and the basic conditions of agricultural production are relatively poor.

The general region is far from the Yellow River, and it is also the leading area of urban development in Mengjin County. Agricultural production in the area is limited by ecological factors, with a long history of agricultural development and a relatively perfect farmland infrastructure. The irrigated land area is 5462.88 h m^2, accounting for 53.74% of the county's irrigated land area, but there are certain terrain undulations in the area. The dryland area is also widely distributed (Table 2).

Therefore, water resources and topographic conditions are the basic factors affecting cultivated land utilization. Cultivated land regulation in Mengjin County should prioritize water saving, spatial balance and systematic management. On the basis of ensuring ecological security, microgeomorphic transformation should be actively implemented to continuously improve the utilization efficiency of water resources, reduce the proportion of dry land and systematically solve the objective constraints of congenital deficiency.

4.2.2 Cultivated land utilization in different ecological function zones

From the perspective of cultivated land utilization, there are five types of cultivated land utilization in Mengjin County, namely, arable land with rotation of grain and non-grain crops, cultivated land intercropped with forest and grain, abandoned arable land, cultivated land for growing nonfood crops, and arable land for growing food crops. The cultivated land without any grain production function is divided into two types, namely, abandoned arable land and cultivated land for growing nonfood crops. The area of abandoned arable land is 717.07 h m^2, mainly distributed in the towns of Matun, Chaoyang and Pingle near the urban area of Luoyang in southern Mengjin. The cultivated land area for nonfood crops is 2135.68 h m^2, mainly distributed in southern Xiaolangdi, eastern Baihe, western Huimeng and the central region of Songzhuang. The spatial distribution of cultivated land use in Mengjin County is shown in Figure 5.

The rates of "non-grain" cultivated lands, which completely lack a food production function, are 7.66%, 8.93% and 10.38% in the extremely important, relatively important and general regions of Mengjin County, respectively.

Most of the cultivated land in the extremely important area is developed from the Yellow River tidal flat, with relatively flat terrain, sparse villages, and large average plot areas and wherein mechanized cultivation is convenient, which can realize the scale benefit of grain cultivation to a certain extent. Therefore, the degree of non-grain conversion of cultivated land in the

TABLE 2 Land type structure of cultivated land in different ecological function areas (hm²).

Type	Paddy fields	Irrigated land	Dry land	Total
Extremely important regions	548.60	2016.60	760.06	3,325.26
Relatively important regions	404.43	2687.02	8363.96	11455.41
General regions	18.10	5462.88	9725.77	15206.75
Total	971.13	10166.5	18849.79	29987.42

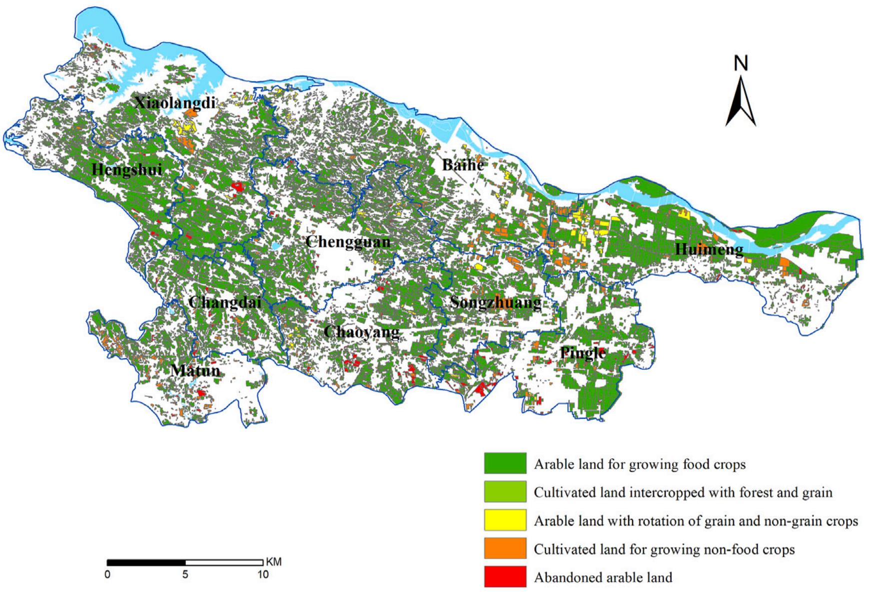

FIGURE 5
Spatial distribution of cultivated land utilization in Mengjin County.

extremely important area is relatively low. Some of the cultivated land in the important area is restricted by the terrain, the farmland facilities are not perfect, mechanical operation is inconvenient, and the benefits of planting food crops are generally low; in those areas, some farmers adapt by cultivating vegetables, medicinal materials, forest fruits and other cash crops, and most of the farmers improve their economic benefits of agricultural production through grain and non-grain crop rotation. The area of arable land with a rotation of grain and non-grain crops in this region is 366.02 h m^2, accounting for approximately 52.13% of the total grain and non-grain rotation areas in the county.

In general, in areas affected by urban industrialization, cultivated land is constantly being converted into construction land, and some farmers convert their cultivated land into facilities for growing flowers or sightseeing destinations to maintain their operating profits. Due to the large number of opportunities for nonagricultural labor, many farmers are also induced to convert their cultivated land to forestland or completely give up cultivation and utilization of their land. The area of abandoned arable land in this region is 480.54 h m^2, accounting for 67.01% of the uncultivated land area in the county, as shown in Table 3.

Therefore, accelerating the mechanization transformation of hilly and mountainous farmland, supporting the construction of grain processing facilities, extending the industrial chain, implementing large-scale and brand projects, and improving grain management benefits are important ways to reduce the non-grain conversion rate of cultivated land.

4.2.3 Landscape structure of cultivated land in different ecological function areas

Due to the influence of topography and tillage patterns, there are great differences in the spatial structure and distribution form of cultivated land in different ecological function areas. The landscape pattern index could effectively reflect the detailed differences in cultivated land use form in different ecological function areas. The number of patches (NP) and average patch AREA (area-MN) are selected to characterize the patch size in Fragstats 4.2. Patch dispersion is characterized by ENN-MN and AI, and patch density (PD) and the landscape shape index (LSI) are used to characterize patch complexity.

As extremely important regions account for only 14.24% of the county's land area, there are only 491 cultivated patches in ecologically important areas. Most of the cultivated land in the extremely important regions is developed from tidal flats. The

TABLE 3 Utilization of cultivated land in different ecological function areas in Mengjin County (hm^2).

Type	Arable land with rotation of grain and non-grain crops	Cultivated land intercropped with forest and grain	Abandoned arable land	Cultivated land for growing nonfood crops	Arable land for growing food crops	Total
Extremely important regions	135.24		24.97	229.72	2933.88	3,323.81
Relatively important regions	366.02	0.21	211.56	811.74	10071.51	11461.04
General regions	200.87	2.82	480.54	1,094.23	13424.12	15202.58
Total	702.13	3.03	717.07	2135.68	26429.51	29987.42

average scale of the farmlands is large, and the shapes of the farmlands are relatively regular. Historically, few rural settlements have been sited in tidal areas, so the degree of concentration of farmland patches is relatively high.

The general regions area concentrated in the urban development area in Mengjin County. The cultivated land in the area is very fragmented by villages and roadways. As villages are developed, the cultivated land patches are constantly being fragmented and usurped by construction land, and the landscape shape index of cultivated land patches becomes more complex. The relatively important regions are in the transition zone between the extremely important regions and the general regions, and the cultivated land landscape pattern index in this region has an intermediate value. In addition, because the Yellow River channel passes through the ecologically important area, the cultivated land in the ecologically important area is distributed on both sides of the Yellow River, resulting in the maximum average nearest distance (ENN-MN) of the cultivated land patches in the ecologically important area, as shown in Table 4.

The landscape pattern index of cultivated land reflects the overall spatial characteristics of cultivated land use in the region. Land consolidation in the main grain-producing areas should reduce the discreteness and complexity of cultivated land patches as much as possible and improve the scale efficiency of cultivated land use through consolidation. Land consolidation in urban development areas should be combined with urban landscape construction to improve the compound function of cultivated land. In the ecological core area, human disturbance should be reduced as much as possible to maintain the integrity of the natural landscape.

4.2.4 Spatial adjacency of cultivated land in different ecological function zones

The spatial adjacency features of the patches can be used to explore spatially dependent paths, interaction intensity, and symbiotic or causal patterns between patches from massive amounts of spatial data. The higher the contiguous ratio between the patches and a certain land type, the stronger the correlation between the patches and the land type. If the contiguous ratio between a certain land type and the cultivated land is higher than 50%, it means that most of the cultivated land is surrounded by that land type, and it also indicates that the land lot and the cultivated land have a high possibility of conversion.

In the extremely important regions, the two land types with the largest contiguous proportions of cultivated land are other agricultural land and forestland because most of the cultivated land in this area is developed from the beach area, and there are a large number of pits and breeding ponds in the low-lying, cultivated land areas of the beach area. In addition, there is a large amount of unused land area in the beach area, a large amount of shrub land is distributed around the unused land, resulting in other agricultural land, and forestland is the largest adjacent land category of the cultivated land in this region.

In the relatively important regions, the two types of adjacent arable lands with the largest proportions are forestland and other agricultural land. This is because relatively important regions are traditionally agricultural production areas. When the benefit of grain planting is low, it is common for farmers to convert arable

TABLE 4 Landscape pattern index of cultivated land with different ecological functions in Mengjin County.

Type	NP	PD	LSI	AREA-MN	ENN-MN	AI
Extremely important regions	491	14.8373	24.1216	6.7398	68.7835	95.9720
Relatively important regions	4,721	41.4082	101.0604	2.4150	46.6981	90.6180
General regions	9782	64.6681	111.5002	1.54564	41.2995	91.0056

TABLE 5 Spatial adjacency of cultivated land in different ecological function zones in Mengjin County.

Type	Garden land (%)	Forestland (%)	Grass (%)	Other agricultural land (%)	Construction land (%)	Unused land (%)	Total (%)
Extremely important regions	7.73	23.76	2.59	44.87	12.53	8.52	100
Relatively important regions	12.35	48.63	5.03	21.52	12.20	0.27	100
General regions	14.32	31.38	3.42	21.38	29.48	0.02	100

land to agricultural facility land. Farmers also convert farmland to forestland more often, resulting in a high proportion of farmland adjacent to forestland and other agricultural land.

The general regions are the core area of urban spatial development, where all kinds of construction land and cultivated land are interlaced. Under the guidance of a large-scale territorial space greening policy, a large number of landscape forest belts are planted on both sides of the main roadways, resulting in a high proportion of cultivated land, forestland and construction land adjacent to this area, as shown in Table 5. It can be known that the policy coordination between management departments is an important way to prevent disordered non-food.

The spatial adjacency characteristics of the patches are important indicators of suitability for a certain land type. If the cultivated land is adjacent to wetland shrubs and the adjacent boundary is greater than 50%, it is feasible to restore the plot to wetland shrubs. Similarly, if the degree of adjacency between cultivated land patches and other agricultural land exceeds 50%, it means that the reclamation of other land interspersed in the cultivated land is also highly feasible. Therefore, in the process of land consolidation, on the premise of ensuring ecological security, some of the other fine patches within the cultivated land can be converted to cultivated land to reduce the degree of fragmentation of cultivated land and improve the scale efficiency of cultivated land use.

4.3 Regulation and control of cultivated land in different ecological function areas

At present, cultivated land utilization in Mengjin County is faced with dual challenges of an increasing degree of "non-grain" cultivation and increasing environmental risks. Guided by the goal of food security, cultivated land regulation in Mengjin County needs to systematically balance production, living and ecological needs by combining the dominant land uses and socioeconomic bases of the region and building a distinct Yellow River ecological system through differentiated cultivated land optimization and regulation to enhance the combined effects of the national Yellow River ecological strategy.

4.3.1 Consolidation of cultivated land in extremely important regions

The total area of cultivated land in the extremely important region is 3,325.26 h m^2, accounting for 31.79% of the total area of the extremely important regions. The long-term and large-scale development of the beach area of the Yellow River leads to a sharp reduction in riverside wetlands and the destruction of natural vegetation and bird habitats. Especially after the tidal flat is transformed into cultivated land, improper agricultural utilization brings nonpoint source pollution to the Yellow River tidal area, and the regional ecological function seriously conflicts with the regional land use. Guided by the goal of food security, development of wetlands in the region should be strictly controlled, and the existing cultivated land should be "balanced", "recyclable" and "diversified".

Regional cultivated land regulation scheme: Aiming at serving the ecological security of the Yellow River Basin, the development of unused land in the beach area is prohibited, and the ecological service of cultivated land in the beach area is comprehensively improved through comprehensive regulation. The ecological function restoration of the Yellow River tidal area is considered the ultimate goal of regulation and utilization, and the ecological red line is considered the rigid constraint condition. The ecological tillage of 2210.91 h m^2 of cultivated land within the ecological red line is implemented, and the use of chemical fertilizers and pesticides is prohibited. The management of transit power lines is conducted underground, suitable environmental habitats are promoted, and transit power lines to the Yellow River wetlands are reduced to limit disturbance to waterfowl activities.

4.3.2 Consolidation of cultivated land in a relatively important regions

The total area of cultivated land in the relatively important regions is 11455.41 h m^2, accounting for 46.71% of the total area of most important areas.

As a traditional main grain production area, this region has a limited cultivated land base, a high proportion of dry land area, many restrictions on large-scale utilization of the cultivated land, and a weak regional industrial foundation. Under the effect of the urban siphon effect, the long-term single population flow results in frequent cultivated land abandonment. Under the guidance of the goal of food security, comprehensive land consolidation should be carried out to reduce the "non-grain" and "abandoned" use of cultivated land and build high-quality and efficient core areas of grain production.

Regional cultivated land regulation scheme: With the goal of building a core area of regional grain production, the grain production function of "non-grain" and "abandoned" cultivated lands will be fully restored, and 211.56 h m^2 of cultivated land will be prioritized for restoration to grain cultivation. In hilly areas, it is necessary to strengthen the improvement of cultivated land with good natural background conditions but that are inconvenient for cultivation and systematically support farmland infrastructure to lay the foundation for the use of labor-saving machinery and reduce the risk of the cultivated land being marginalized. In plain areas, the reclamation of inefficient construction land should be strengthened, and the adjustment of land ownership should be followed up on according to the transfer of the labor force to actively promote farmland consolidation and create conditions for large-scale farmland construction.

4.3.3 Consolidation of cultivated land in the general regions

The total area of cultivated land in the general area is 15206.75 h m^2, accounting for 39.51% of the total general areas. The urban development and agricultural production spaces in the region are highly superimposed. The cultivated lands near the Luoyang urban area and the Mengjin central urban area are fragmented by construction land, and the proportion of "non-food" use of cultivated land is high. Under the guidance of the national land greening policy, the cultivated land along the roadways is adjusted to forest landscapes on a large scale. Abandonment of cultivated land is more common. Under the guidance of food security goals, we should promote the organic integration of the landscape and production functions of cultivated land through comprehensive land consolidation and improve the food production function of cultivated land.

Regional cultivated land regulation plan: Fully abiding by the principle of matching rural production activities with landscape value and function orientation, promote the composite utilization of cultivated land, and prioritize the restoration of 480.54 h m^2 of abandoned arable land to grain use. In the urban and rural interleaving farmland area, it is necessary to continuously expand spaces for leisure and sightseeing of beautiful farmlands, comprehensively improve the farming experience, ecological conservation, tourism and leisure and other diversified living functions of cultivated land, and promote the transformation of abandoned farmland to "shared farmland" and "shared manors" based on a socialization platform in accordance with the concepts of advancement and replacement to restore the food production function of cultivated land. In addition, the efficiency of resource utilization should be improved. In the farmland area outside the town, around the construction of a beautiful countryside, the cultivation of "high quality, high yield and high efficiency" farmland should be strengthened.

5 Discussion

5.1 Prioritizing the restoration of abandoned farmland for grain use

Due to the influence of land greening policies, it is common to convert cultivated land to forestland around towns and on both sides of roadways, thus increasing the amount of "non-grain" cultivated land. If the land that has been transformed into forestland is adjusted and restored to arable land, it will not only waste a large amount of funds but also cause damage to the ecological environment to a certain extent.

Therefore, under the goal of food security, the primary goal of land consolidation in Mengjin County is to reduce the non-grain rate of cultivated land. Through land consolidation and land ownership adjustment, the restoration of abandoned cultivated land in general ecological areas and in more important ecological areas for grain use and delaying the marginalization process of cultivated land should be prioritized. In this way, the food supply capacity can be maximally enhanced, and the basic interests of farmers can be maintained without causing damage to the ecological environment.

5.2 Strictly control "nonfood" use of cultivated land

The dietary structure of people in urban and rural residential areas shows a trend of a reduced proportion of main grains and increased diversification. Therefore, under the guidance of food security goals, the concepts of "big agriculture" and "big food" should be established. These should not only meet people's total energetic intake demand but also meet the increasingly diversified food consumption demand and improve the food security ability in a multidimensional way. Therefore, it is necessary to recognize how much "non-food" cultivated land is reasonable, allow a reasonable "food" use of cultivated land, strictly forbid the structural adjustment of cultivated land to "nonfood" purposes, and resolutely prevent the conversion of cultivated land to forestland and landscapes.

5.3 Coordinate policies among departments

It is important to promote the modernization of farmland management systems to promote the coordinated energy efficiency of farmland protection management. In the past, the relevant state departments lacked a systematic understanding of ecological civilization construction and believed that increasing the forest coverage rate was a good policy for promoting ecological civilization construction. Through governments at all levels, large-scale greening projects were implemented on both sides of expressways, national roads, provincial roads and even county roads that helped to promote "non-grain" cultivated land to a certain extent. Policy coordination among departments, therefore, focuses on the local-scale governance of marginalized farmland recovery, mainly on policies at a regional scale, through the promotion of a regional ecological function in coordination with a food safety supply regulation mode, realizing the organic combination of ecology and the industrial chain.

5.4 Ecological utilization of cultivated land in beach areas

A total of 66.48% of the cultivated land in the extremely important region is within the ecological red line. With its large scale, high degree of mechanization and low proportion of non-grain production, the cultivated land in the beach area is the production area of high-quality agricultural products in Mengjin County. If all the cultivated land is withdrawn from use, it will inevitably have an adverse impact on food safety production and a great impact on the livelihood of regional farmers.

Therefore, ecological farming in beach areas is an important way to resolve the conflicts between food safety production and ecological environment protection. Strict implementation of ecological farming in beach areas requires the allocation of corresponding planting structures according to the site conditions of the region and the reduction of human interference to the greatest extent through systematic control.

Income is an important factor affecting whether farmers adopt ecological farming. Therefore, in the near future, some suitable plots can be transformed into lotus ponds or fish ponds with wetland functions, and ecological tourism based on wetland bird watching, lotus pond rafting and fish pond fishing can make up for part of the loss of ecological farming. Under current farming conditions, most farmers tend to use chemical fertilizers and pesticides to maintain stable farming benefits, and corresponding control policies are needed to promote ecological farming in beach areas. To maximize the value of ecological agricultural products, we need to rely on the regionalization of agricultural distribution, the scale of operation, and the industrialization of products and overcome the value loss caused by ecological farming with standardized management.

6 Conclusion

(1) Guided by the goal of food security, the regulation and control of cultivated land in different ecological function zones in Mengjin County should fully connect with the national Yellow River Strategy and be carried out in different zones and categories based on the regional ecological red line, farmers' development needs and the difficulty of making changes.

In the extremely important regions, the restoration of the ecological function of the Yellow River beach should be the ultimate goal of regulation and utilization, ecological farming of the beach land should be implemented, development of the beach wetland should be strictly controlled, and human disturbance should be reduced. In the relatively important regions, we should make full use of the existing cultivated land to ensure that more land does not become abandoned. Land consolidation should be strengthened, farmland infrastructure should be systemically supported, and combined with the adjustment of farmland ownership, and land consolidation should be actively promoted to create conditions for large-scale farmland construction. In the general regions, the principle of matching rural production activities with landscape value and function orientation should be fully observed, and the composite utilization of cultivated land should be promoted.

In the face of the surging consumption of high-end agricultural products, we should expand the space for leisure and beautiful agricultural land and promote the construction of "shared farmland" and "shared manors" in a timely way, promote the high-quality integrated development of urban and rural areas, pay attention to the landscape construction of large-scale farmland, and establish a more reliable food security base. This regulation scheme can guarantee grain safety production to the greatest extent and effectively enlarge the ecological and environmental effects of land consolidation.

(2)The low economic benefit is an important reason for the "non-grain" of cultivated land. However, due to the significant difference in production efficiency between non-grain crops and grain crops, farmers with a larger scale of land management prefer to plant grain crops. In the ecologically extremely important regions, uncultivated land is small and scattered, so it should be guided to implement "rewilding" utilization of uncultivated land in this regions. In ecologically relatively important regions, land transfer should be actively guided for uncultivated land, and large-scale and brand-oriented projects should be implemented through machine-oriented transformation of farmland in hills and mountains to comprehensively improve the scale benefits of non-grain planting. For cultivated land planted with vegetables and medicinal materials, industrial layout planning should be further improved to strengthen the agglomeration effect of cash crop planting. In the ecological general regions, the abandoned farmland should be restored for food use by developing substitute farming or sharing and experiential agriculture. For the cultivated land planted with flowers and nurseries in the region, we should actively develop water-saving urban agriculture and improve the water efficiency of facility agriculture.

(3)With the government's increasing focus on the ecological protection of the Yellow River basin, most of the tidal flats along the Yellow River have been included in the ecological red line. However, due to the disordered development of tidal flats throughout history, there is a large area of cultivated land in the tidal area of the Yellow River, resulting in the conflict between ecological protection and food production. The Mengjin beach area is only a small part of the Yellow River beach area; if the Yellow River beach area is blindly restored into farmland, it will have a certain impact on the national food security supply; therefore, the implementation of ecological farming is an important way to solve the ecological protection and food security production. Currently, the compilation of national spatial planning should reflect the requirements of the national spatial development strategy, coordinate the relationship between food security, ecological civilization and sustainable development, use the consistency of national spatial management and control as guidance, reasonably delimit ecological, urban construction and agricultural development spaces, and optimize the management and control mode of spatial resources. This will ensure that the results of territorial space planning are forward-looking and scientific, improve the effectiveness of the work of relevant government administrative departments, and reduce the contradiction between multiple plans and joint management.

(4)The ecological red line is an important system for ecological environmental protection in China. In the process of delineating the ecological red line, the competent authorities often include the important, sensitive and vulnerable territorial space within the region into the red line, so as to maintain the basic ecosystem structure and function. In the arid and semi-arid areas of central and western China, most rivers, lakes and reservoirs and their surrounding areas are included in the ecological red line and strictly controlled, resulting in the dilemma of excellent agricultural conditions and shortage of irrigation water. How to support national food security and maintain the healthy development of ecological environment with limited water resources? It is one of the bottleneck problems that need to be solved urgently. The ecological red line is not a barrier to the tension between man and nature, nor is it a universal line to solve ecological problems. To establish an ecological civilization in which human beings coexist in harmony with nature, water resources should be regarded as the biggest rigid constraint. Under the premise of comprehensively considering the requirements of national food security, factors such as water resources conditions, farmland output capacity, irrigation capacity and level should be fully considered to scientifically determine the grain output of the basin and follow the concept of ecosystem services. In order to ensure that the withdrawn irrigation water plays its role in ecological protection, it is necessary to strictly control the expansion of irrigation area, introduce or improve relevant policies and measures, and promote the coordination of various functional departments in agricultural water-saving and ecological protection.

Based on the dominant space and social and economic basis of cultivated land in different ecological functional areas, this study systematically balanced people's demands for production, living and ecological functions of cultivated land in different locations, took the safe supply of food as the target, and comprehensively considered the multifunctionality of cultivated land utilization, and proposed the remediation and optimization regulation paths of cultivated land in different ecological functional areas. This study improves the result instability caused by selecting cultivated land function evaluation index to measure cultivated land multifunction and function balancing. It enriched the research system of cultivated land multifunction, and provided a scientific basis for optimizing and adjusting the relationship of cultivated land multifunction according to local conditions under the guidance of food security goals.

Based on the conclusion of this study, the following policy suggestions are put forward: ① The cultivated land within the ecological red line should take into account ecological protection and agricultural production issues, avoid "one-size-fits-all", implement the management mechanism of "functional zoning + control rules", clearly prohibit the use of pesticides and fertilizers, and the cultivated land management system oriented by leading functions is fully implemented. ② To establish a comprehensive view of big food, we should acknowledge the practical needs of food diversification. The "non-grain" prevention and control of cultivated land is mainly to control the abandonment of farmland and planting trees, so as to avoid excessive adjustment to the direction of grain and harm to the vital interests of farmers.③ The policy in-coordination between management departments is also an important reason for the cultivated land "non-grain", large-scale greening projects have caused the high-quality cultivated land along the traffic line to be adjusted to forest land, and the policy coordination between management departments is the basic condition to ensure the management of cultivated land "non-grain". ④ The future land consolidation work should change the previous tendency of paying too much attention to improving the quality of cultivated land, and the focus of work should be shifted to ownership adjustment, through which large-scale cultivation of cultivated land should be promoted. At the same time, the overall policy of land allocation by water should be implemented. All irrigated farmland should be reformed for efficient water saving, and the development scale of irrigated area should be strictly controlled to achieve both water saving and efficiency improvement.

Data availability statement

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

Author contributions

In this paper, XG processed the data and wrote the main contents of the paper. XW, JZ, and ZD provided ideas for the paper. All authors contributed to the article and approved the submitted version.

Funding

This work was supported by the National Natural Science Foundation of China (Grant No. 42101309), Humanities and Social Science Project of Ministry of Education (Grant No. 20YJCZH037), Henan Provincial Scientific and Technological Innovation Talents Support Program (Grant No. 2021-CX-052), Philosophy and Social Science Planning Project of Henan Province (Grant No. 2022BJJ110) and Key Project of Fundamental Research of Philosophy and Social Sciences in Universities of Henan Province (Grant No. 2023-JCZD-21).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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frontiers | Frontiers in Environmental Science

TYPE Review
PUBLISHED 18 September 2023
DOI 10.3389/fenvs.2023.1175239

OPEN ACCESS

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RECEIVED 27 February 2023
ACCEPTED 06 September 2023
PUBLISHED 18 September 2023

CITATION
Zhao Z, Lei M, Wen L, Xie E and Kong X (2023), Research status, development trends, and the prospects of cultivated land risk.
Front. Environ. Sci. 11:1175239.
doi: 10.3389/fenvs.2023.1175239

Research status, development trends, and the prospects of cultivated land risk

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Cultivated land risk poses a critical threat to food security, and managing it is crucial for sustainable land use. To effectively manage this risk, it is essential to identify different types of cultivated land risk, understand their development trends, and research hotspots. This review constructs a comprehensive search strategy for subject terms in CiteSpace to analyze 12,581 literature sources related to cultivated land risk. Through tracking hot spots in cultivated land risk research, we have identified two main phases over the past 20 years. The first phase (2002–2015) focused on exploring various types of cultivated land risk, including soil, nitrogen, sewage sludge, organic matter, and carbon sequestration. Three keywords:soil, nitrogen, and sewage sludge were studied extensively during this period, with research on agricultural intensification, transport conservation, all aimed at enhancing the theoretical framework concerning cultivated land risk. The second phase (2015–2022) emphasized in-depth research into the mechanisms behind the generation of cultivated land risk. Key topics included methods and models for cultivated land risk research, source analysis, and source apportionment, as well as potentially toxic element and random forest analyses. This phase saw a shift towards a more comprehensive understanding of cultivated land risk, with a focus on uncovering underlying causes and developing effective mitigation strategies. Our research has identified three pivotal steps aimed at reducing cultivated land risk: 1) Rigorous Land Use Management: Implement stringent land use regulations to safeguard high-quality land resources. 2) Sustainable Agricultural Practices: Curtail the utilization of chemical fertilizers and pesticides, fostering improved soil fertility and minimizing environmental repercussions. 3) Robust Environmental Oversight: Establish a robust monitoring network to consistently track environmental concerns, concurrently encouraging the adoption of eco-friendly farming techniques. This comprehensive review holds substantial theoretical significance in advancing the agenda of sustainable cultivated land management and effectively alleviating the perils linked with land use alterations.

KEYWORDS

cultivated land risk, literature review, CiteSpace, planetary boundaries, cultivated land use system

1 Introduction

Cultivated land is an important strategic resource to ensure food security and social stability. Effective cultivated land production can make a significant contribution to solving the feeding problem of 7 billion people worldwide. However, the process of cultivated land use is inevitably accompanied by material and energy input. To obtain as much food as possible on a piece of land, producers often use a large number of pesticides and chemical fertilizers that generates serious ecological and environmental problems to both the cultivated land itself and the surrounding environment. Studies have found that global yield changes are largely controlled by fertilizer use, irrigation, and climate (Mueller et al., 2012). Cultivated land use systems are a key influence on global degradation (Foley et al., 2005; Foley et al., 2011). By 2050, land degradation and climate change are projected to combine to reduce global crop yields by an average of 10%, and in some regions by as much as 50%. It could force 50–700 million people to migrate, threatening the livelihoods of at least 3.2 billion people globally (IPBES, 2018). How to maintain sustainable high and stable food production and ensure food security while minimizing environmental impacts has been one of the century's challenges for scholars and policymakers (Foley et al., 2011), so it is very meaningful to study the types, causes and control methods of cultivated land risk, which provides an important research basis for promoting sustainable use of cultivated land.

In an early study, Stevens et al. (1997) studied cultivation-wildlife conflicts in Western Europe, and most of its regions are characterized by agriculture as an important land use. For example, birds (Rolstad et al., 2000; Thiollay, 2006; Collard et al., 2009; Mzendah et al., 2015), wild boars (Amici et al., 2012; Hua et al., 2016; Liu et al., 2019), and insects (Forister, 2009; Cancela and Sarkar, 1996) have become important external risk factors that threaten the productive use of cultivated land. However, with the increase of urbanization and industrialization, such risks have been gradually replaced by risk types such as heavy metal pollution of soil, and a large number of studies have based on Multivariate statistical analysis, Positive Matrix Factorization receptor modeling techniques (Guan et al., 2018), Principal component analysis (Xiao et al., 2015), and Integrated Model (Marrugo-Negrete et al., 2017; Huang et al., 2018; Hu et al., 2017; Wang et al., 2019) to measure the heavy metal pollution status of cultivated land. The study of cultivated land risk gradually developed from qualitative analysis to the path of combining quantitative and qualitative analysis, but at this stage, the study of cultivated land risk still remained at the element level and failed to discover the uncoupled linear relationship between elements and systems, until Rockström et al. (2009) proposed a planetary boundary framework, and cultivated land risk studies began to focus on systematics-based studies with declining groundwater (Kong et al., 2016; Rodell et al., 2018), increasing nitrogen and phosphorus emissions (West et al., 2014; Schulte-Uebbing et al., 2022), and increasing greenhouse gas emissions (Carlson et al., 2017; Hu et al., 2020). Other external risks arising from cultivated land use systems are receiving more and more attention from scholars. In recent years, there has been a noticeable surge in the number of papers and reviews concerning cultivated land risk. However, the current research landscape on cultivated land risk exhibits fragmentation and a lack of integration with other systematic theories in land science. Additionally, there exists a deficiency in quantitative analyses of cultivated land risk, along with inadequate development of effective risk management strategies and control pathways. To address these shortcomings and advance the field, it is imperative to incorporate new models and methodologies into the study of cultivated land risk. By doing so, we can enhance the accuracy of research outcomes while also elucidating the various types and underlying causes of risk. This, in turn, will contribute to the promotion of sustainable cultivated land utilization.

Therefore, through the CiteSpace approach, this study attempts to systematically analyze the basic situation, management strategies, development trends, and hot issues of cultivated land risk research, focusing on the following issues.

(1) What are the general dynamics of cultivated land risk research?
(2) What are the salient phases and hot topics of cultivated land risk research?
(3) How has the methodology and management strategy for cultivated land risk research evolved?
(4) What are the challenges and future directions of the cultivated land risk?

2 Data and methods

The literature data in this article were obtained from the core collection of the Web of Science database (https://www.webofscience.com/, accessed on 25 November 2022). The Web of Science is an important database for accessing global academic information. It contains more than 13,000 authoritative and high-impact scholarly journals worldwide, covering a wide range of fields such as natural sciences, engineering and technology, biomedicine, social sciences, arts and humanities. The web of Science includes references cited in papers. Through the unique citation index, users can use an article, a patent number, a conference paper, a journal, or a book as search terms to retrieve their citations and easily retrace the origin and history of research literature or track its latest progress; the more extensive, newer and deeper the search, the more in-depth the search can be.

This paper analyzes the knowledge graph through CiteSpace, a data mining and visualization analysis software jointly developed by Professor Chaomei Chen of the School of Information Science and Technology at Drexel University and the WISE Lab of the Dalian University of Technology. By extracting and analyzing subjective information such as keywords, subject terms, authors, and institutions, the software can mine the underlying information and visualize the interrelationships between related information and information entities through visual knowledge graphs. The software can also reveal the development status of scientific knowledge in a certain field by showing the development trend of a certain science or knowledge field in a certain period through the convergence of related information. It is commonly used in information science, economics, sociology, and many other fields.

The accuracy and comprehensiveness of data retrieval guarantee the accuracy of CiteSpace's operation. In practical literature retrieval, it is often relatively challenging to simultaneously ensure both accuracy and comprehensiveness. To maximize the accuracy of data analysis results, we can refer to the article published by Professor Chen Chaomei in 2017. Following his advice, the primary consideration in data retrieval should be

TABLE 1 Comprehensive search rules for cultivated land risk subject terms based on Web of Science core dataset.

Set	Results	Retrieval rule	Database
#1	9868	cultivated land (**Topic**) AND Article OR Review (**Document Type**) AND English (**Language**)	Web of Science Core Collection
		Timespan: 2002-01-01 to 2022-11-25	
#2	7962	arable land (**Topic**) AND Article OR Review (**Document Type**) AND English (**Language**)	Web of Science Core Collection
		Timespan: 2002-01-01 to 2022-11-25	
#3	16504	farmland (**Topic**) AND Article OR Review (**Document Type**) AND English (**Language**)	Web of Science Core Collection
		Timespan: 2002-01-01 to 2022-11-25	
#4	13883	cropland (**Topic**) AND Article OR Review (**Document Type**) AND English (**Language**)	Web of Science Core Collection
		Timespan: 2002-01-01 to 2022-11-25	
#5	58090	agricultural land (**Topic**) AND Article OR Review (**Document Type**) AND English (**Language**)	Web of Science Core Collection
		Timespan: 2002-01-01 to 2022-11-25	
#6	89021	#1 OR #2 OR #3 OR #4 OR #5	Web of Science Core Collection
#7	3262809	"ris*" (**Topic**) AND Article OR Review (**Document Type**) AND English (**Language**)	Web of Science Core Collection
		Timespan: 2002-01-01 to 2022-11-25	
#8	12581	#7 AND #6	Web of Science Core Collection

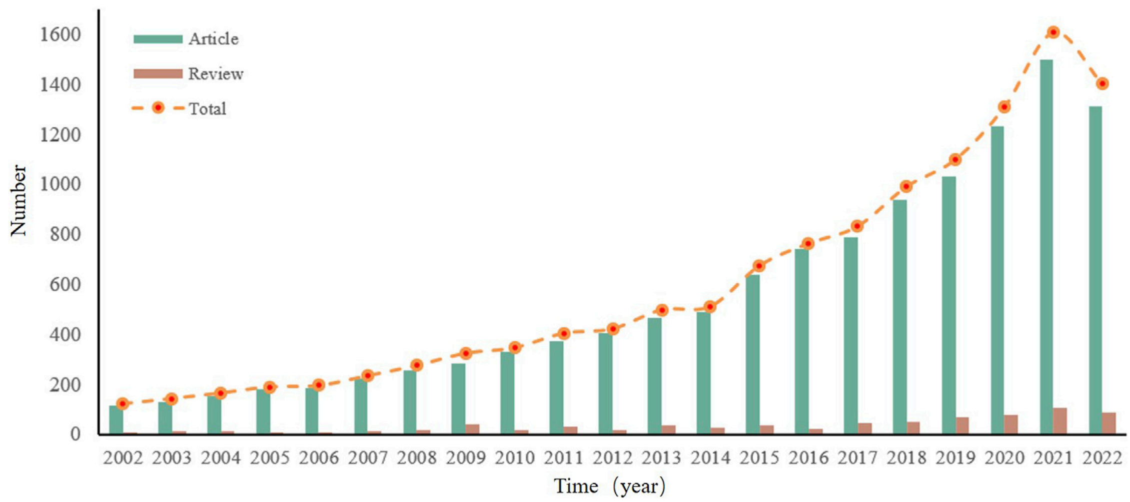

FIGURE 1
The quantity distribution trend of literature on cultivated land risk from 2002 to 2022.

comprehensiveness, as CiteSpace software automatically removes irrelevant or duplicate information during the data processing (to enhance accuracy). Therefore, in this paper, we established a "comprehensive search strategy for subject terms" to obtain the original data more scientifically and comprehensively, as shown in Table 1. We used the latest CiteSpace.6.1. R3, with a time slice of 1 year, and the node selection method of g-index, where k = 25/10; the choice of node type determines the purpose and main focus of our analysis using CiteSpace, in this study, to explore the regression changing characteristics of cultivated land risk development, we mainly used the keyword co-occurrence analysis method to conduct a macro visualization study of 12581 literature records to obtain the co-occurrence network, which can further discuss the development pulse of the literature.

3 Bibliometric analysis of cultivated land risk research based on CiteSpace

3.1 Subject analysis based on the dual map overlay

We assessed the number and trend of literature publications on cultivated land risk studies from 2002 to 2022 (Figure 1). Overall, the

10.3389/fenvs.2023.1175239

TABLE 2 Main countries involved in cultivated land risk literature publication.

Rank	Number of articles	Country	Centrality[a]	Sigma[b]
1	3204	China	0.02	1.00
2	2663	United States	0.18	8.21
3	1130	England	0.08	24.36
4	1019	Germany	0.14	1.00
5	811	Australia	0.1	1.00
6	607	Italy	0.05	1.00
7	595	Canada	0.05	1.00
8	529	Spain	0.07	1.25
9	525	France	0.13	2.10
10	495	Netherlands	0.07	1.79

Note: [a]Centrality is an indicator to measure the importance of nodes in the network. The larger the value of centrality is, the more the number of publications cooperated with other countries.
[b]Sigma is used to identify innovative literature and can be used to identify innovative topics (Chen, 2004; Chen et al., 2009; Chen and Song, 2019).

literature on cultivated land risk showed a fluctuating upward trend in the past 20 years, increasing from 122 in 2002 to 1401 in 2022. Based on the number of publications in different years, we broadly divided the research on cultivated land risk into two stages of change: 1) Steady development-steady increase stage (2002–2014), during which the literature on cultivated land risk research began to develop and show a more obvious trend of increase. 2) The rapid development-stabilization phase (2014–2022), during which the literature on cultivated land risk has increased rapidly and different countries, research institutions and scholars have started to focus on the impact of cultivated land risk from different research perspectives, and have conducted a series of research works. While there is a substantial disparity in the number of articles published in “Review” and “Article,” it is evident that the number of articles published in “Review” has been steadily increasing year by year. Starting with just 8 articles, this number has grown to 87 articles in 2022, representing an almost 91% increase. This trend suggests a significant rise in the quantity of reviews and articles addressing cultivated land risk.

Based on the Web of Science core dataset, we found that the top ten countries conducting the most research on cultivated land risk by the end of 2022 are China, the United States, the United Kingdom, Germany, Australia, Italy, Canada, Spain, France, and New Zealand (Table 2). Among them, China, the United States, the United Kingdom, and Germany all have more than 1000 publications, with China having the largest number of publications at about 3204, followed by the United States with about 2663, but the United States has the highest intermediary centrality at about 0.18, indicating that the United States collaborates more frequently with other countries in publishing environmental risk literature; although China has the largest number of publications, its intermediary centrality is the smallest at 0.02, indicating that Chinese researchers are more inclined to intra-national communication and cooperation when publishing relevant literature. The Sigma metric reveals substantial discrepancies between the UK and the US compared to other nations. Remarkably, the Sigma value for the UK surpasses that of all other countries, with a notable threefold disparity compared to the US, measuring around 24.36. The Sigma value for the US stands at approximately 8.21. In contrast, the remaining countries exhibit Sigma values ranging between 1.0 and 2.1. Despite the UK publishing only half the number of articles compared to the US, this discrepancy underscores the superior quality of the UK’s research contributions in the realm of cultivated land systemic risk. This observation underscores that the UK outperforms other nations not only in terms of publication quality but also in terms of innovation. This exceptional performance can potentially be attributed to the collaborative nature of research endeavors between the UK, the US, and international researchers. This emphasis on cross-border collaboration likely contributes to their capacity to attain innovative outcomes in their investigation of arable land risk, as evidenced by the centrality indicator.

The construction of the disciplinary analysis network is based on the dual map overlay of CiteSpace software, and the consequences of the dual map overlay show the position of the cultivated land risk relative to the main research disciplines. The dual-map overlay analysis provides readers with an overarching view of the fields encompassed by the research direction. It allows us to observe the disciplinary domains within which the citing and cited journals are situated. This approach is particularly useful in identifying potential interdisciplinary intersections within the research direction. The z-scores function highlights stronger and smoother trajectories, and higher index values are represented by thicker lines. It can be seen that publications in the field of “ecology, earth, ocean” (blue trajectory) are mainly dominated by “botany, ecology, zoology ($z = 6.97$, $f = 17338$)”, “environment, toxicology, nutrition ($z = 2.97$, $f = 17338$)”, “environmental science, toxicology, and the environment, Nutrition ($z = 2.72$, $f = 7309$)”, “Earth, Geology, Geophysics ($z = 3.42$, $f = 8979$)”, and “Economics, Policy ($z = 2.05$, $f = 5712$)”. In addition, publications in the field of “Veterinary medicine, animals, science (yellow trajectory)” were mainly influenced by “Botany, ecology, zoology ($z = 4.45$, $f = 11383$)”, “Environment, toxicology, nutrition ($z = 3.57$, $f = 9308$)”. It can be seen that cultivating land risk research involves several subject areas. On the whole, cultivated land risk research is based on ecology, geology, environmental science, botany and other disciplines, and

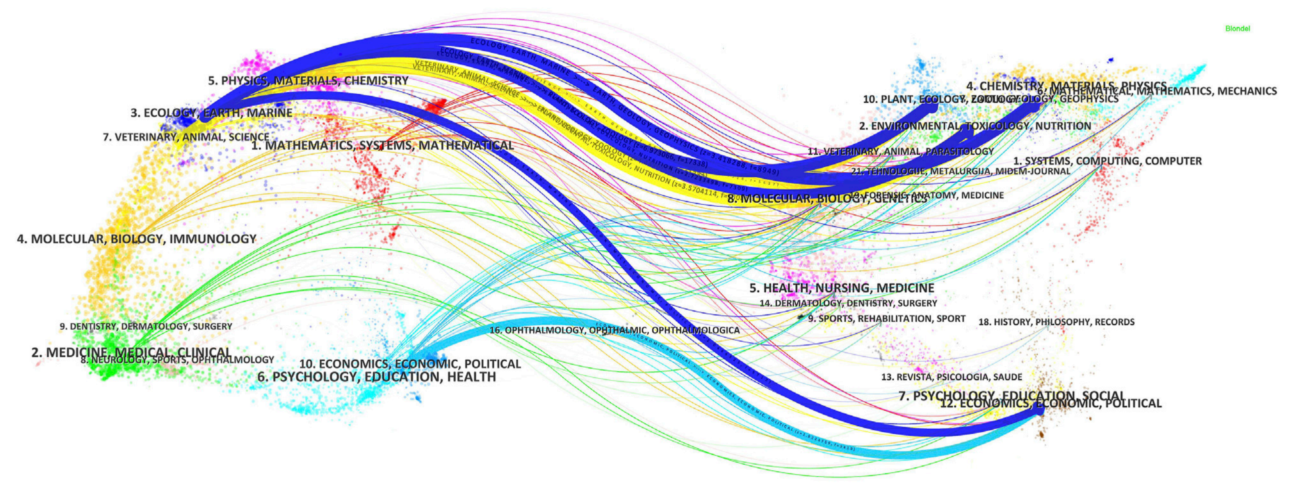

FIGURE 2
Subject Analysis Network of environmental risk research literature based on the dual map overlay.

applied to ecology, earth, ocean, animal and other disciplines, which has strong interdisciplinary nature and is conducive to the integration of multidisciplinary resources and easy to achieve original and major scientific breakthroughs (Figure 2).

3.2 Exploring the research hotspot and evolution trend of cultivated land risk

3.2.1 Keyword hotspots and distribution trend analysis

The core of the analysis is the condensation of keywords. CiteSpace can visualize the keywords and generate a keyword clustering map, based on which the cluster number is the *y*-axis and the year of citation publication is the *x*-axis, the timeline map of keyword clustering can be laid out (Figure 3). The timeline map can show the time span and the research process in the development and evolution of each cluster (i.e., subfield) over the period of 2002–2022. The larger the number of the cluster's serial number, the fewer keywords are contained in that cluster, and conversely, the smaller the number, the more keywords are contained in that cluster. In order to assess the reliability of the bibliographic results. "Modularity value Q)" and "weighted average profile value S)" was set as the evaluation indicators in CiteSpace. It is generally considered that a modularity value Q) > 0.3 and a weighted average profile value S) > 0.7 indicate high reliability of the results (Chen, 2017; Chen et al., 2020), and based on the timeline mapping, it can be seen that the modularity value of the network is 0.4192 and the weighted average profile value is 0.7396, which can be considered as very high, indicating that the cultivated land risk study is well defined in terms of co-citation clustering. The overall complexity of the clustering network indicates that there are still more links between the subcategories of distinct clusters. The timeline diagram shows that the clusters related to the study of cultivated land risk mainly include eight categories: heavy metal, climate change, conservation, water quality, carbon sequestration, remote sensing, land degradation and resource use efficiency. The cluster "heavy metal" has the smallest number and contains the most keywords, which is the largest cluster in the study of cultivated land risk, while "resource use efficiency" is the smallest cluster. These clusters encompass not only the factors contributing to cultivated land risk but also encompass the various risk categories, research methodologies, and prevalent research focal points. Noteworthy within these are ecological risks, ecological risk assessment, greenhouse gas emissions, land expansion, sustainable intensification, and more—each of which holds a significant presence in prominent academic journals.

Remote sensing stands out as a prominent approach in investigating cultivated land risk, offering a plethora of tools. The utilization of remote sensing techniques initially focused on basin-scale assessments, employing classification methods to discern and delve into cultivated land risk. Since 2014, the application of sensitivity analysis, indices, time series analysis, and random forest methods has notably expanded, making substantial contributions to the study of cultivated land risk. These methodologies not only enhance our comprehension of the subject but also lay the groundwork for more refined and comprehensive research endeavors.

3.2.2 Detection and analysis of burst words

Keyword emergence refers to a significant increase in the frequency of keywords in a certain time span, expressed by strength, and the larger the strength value, the higher the emergence intensity, indicating that the keywords are more influential and the hot words in the field of research in that time span (Chen et al., 2009; Chen et al., 2010). The red line in the table indicates the year in which the mutation occurred in the keyword, and the blue line indicates the year in which there was no mutation (Table 3). Based on the CiteSpace hotspot analysis tool we detected the keywords with mutation intensity in the top 20 and sorted them by the year of mutation. We found that mutation words have more obvious phase characteristics. In the first phase (2002–2015), the main types of cultivated land risk explored in this phase were main elements: soil, nitrogen, sewage sludge, organic matter, carbon

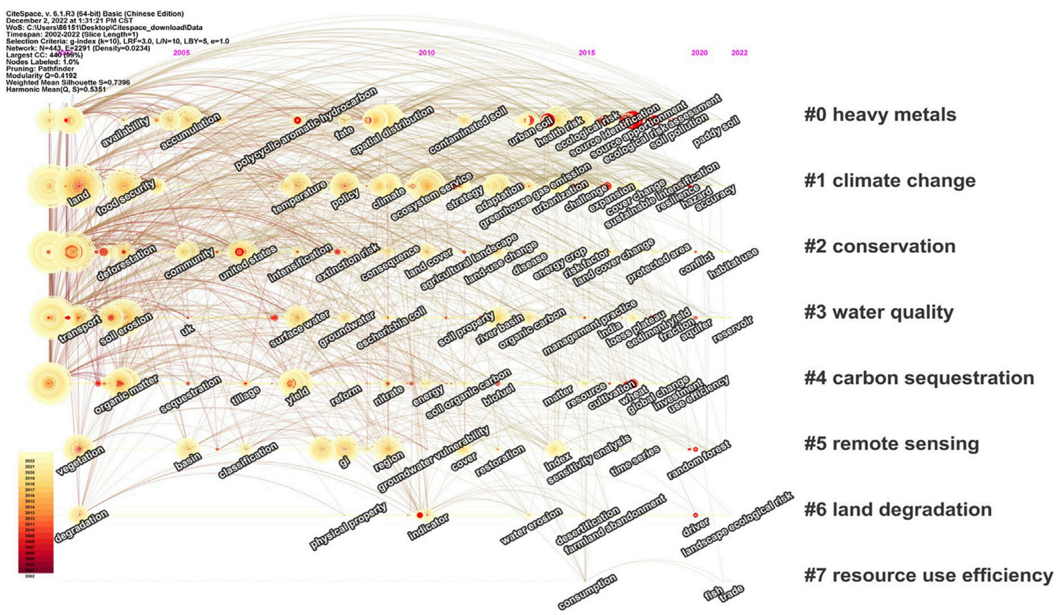

FIGURE 3
Timeline map of cultivated land risk research.

sequestration, etc. Among them, soil, nitrogen, and sewage sludge these three keywords have a long mutation time, spanning from 2002 to 2013. In the past 11 years, the research on the theme of cultivated land risk has been analyzed mainly from three aspects, and we can also see that the words agricultural intensification, transport conservation, and system also become strong mutations in this phase, indicating that the research on the theoretical framework related to cultivated land risk is also gradually strengthened and begins to focus on the drivers and driving factors of cultivated land risk. In the second phase (2015–2022), this phase focuses on cultivated land risk more on the mechanism behind the generation of cultivated land risk for in-depth research, involving methods and models for cultivated land risk research, source analysis, etc., and source apportionment, potentially toxic element, random forest, etc. have been the hot and key topics of cultivated land risk research in the past 5 years.

3.2.3 Cooperation agency network analysis

Mapping of institutional collaboration networks can tell us about the links between institutions and the contribution of each institution in the field of cultivated land risk research, which helps us to identify researchers and institutions that deserve attention. By doing a network analysis of the major research institutions and cultivated land risk research, we found that cultivated land risk research is widely followed in 39 countries and 47 research institutions worldwide (Figure 4). Universities and research institutions have relatively close ties and collaboration. There are ten institutions with more than 100 articles. The Chinese Academy of Sciences occupies a central position in the collaborative network in the field of arable land risk research, with Wageningen University, Beijing Normal University, China Agricultural University, Zhejiang University, University of California, Davis, Agriculture and Agri-Food Canada, Chinese Academy of Agricultural Sciences, and Northwest Agriculture and Forestry University as important links in the network of collaborating institutions. In addition, more fruitful work has been published by research institutions such as Harvard University, Michigan State University, University of Zurich, French National Institute of Agricultural Research, USDA Agricultural Research Service, Illinois State University, and Aarhus University.

4 Hot topics and core fields of cultivated land risk research

4.1 Comprehensive analysis of cultivated land risk studies

As the study of cultivated land risk continues to increase, its connotation becomes richer and richer. In diverse agricultural production and ecosystems around the world, the research methods and control strategies also vary greatly in response to the multidimensional nature of the research scale and the diversity of risk types (Table 4). Current research on cultivated land risk focuses on large scales (world or regional scales), and the types of risks studied at these scales are mainly biodiversity loss, wildlife habitat degradation, etc. Green et al. (2005) used a data analysis approach to assess the risk to wildlife habitat arising from cultivated land use using the FAO bird database, and by examining studies in developing countries suggest that highly productive farming practices may allow for the presence of more species. Contrary to our perception, there does not necessarily represent a trade-off between high yield and maintaining biodiversity, and we can maintain species diversity while maintaining high yields. The study by Mueller et al. (2012) also suggested that sustainable intensification can be effective in achieving control of cultivated land risks. Except for heavy metal pollution (Jiang et al., 2017; Liang et al., 2017; Guan et al., 2018), more effective control measures exist for all other cultivated land risk

TABLE 3 Top 20 keywords with the strongest citation bursts during 2002–2022.

Keywords	Strength	Begin	End	2002-2022
Soil	33.45	2002	2010	
Nitrogen	20.35	2002	2012	
Sewage sludge	20.94	2003	2013	
Transport	13.17	2003	2010	
Conservation	11.58	2003	2010	
Runoff	12.69	2004	2007	
Organic matter	15.05	2004	2010	
United states	17.59	2006	2009	
Agricultural intensification	14.38	2006	2015	
System	12.85	2006	2012	
Tillage	11.54	2006	2009	
water quality	12.94	2007	2012	
Predation risk	12.36	2008	2010	
Carbon sequestration	11.19	2010	2014	
Landscape	10.96	2013	2015	
Maize	11.51	2017	2020	
Sediment yield	11.47	2018	2022	
Source apportionment	14.2	2019	2022	
Potentially toxic element	14.97	2020	2022	
Random forest	12.56	2020	2022	

types, because the problem of soil heavy metal pollution is influenced not only by the process of cultivated land use, but also by regional resource background conditions and industrial and other processes (Chen et al., 2023). Gradually, in order to better assess the impact of cultivated land risk, scholars have slowly focused on characterizing the degree of impact of cultivated land risk through elements such as soil degradation (Lal, 2004), greenhouse gas emissions (Searchinger et al., 2008; Godfray et al., 2010; Foley et al., 2011; Tilman and Clark, 2014; Steffen et al., 2015), freshwater use (Godfray et al., 2010; Steffen et al., 2015), and nitrogen and phosphorus emissions (Steffen et al., 2015). The control strategies for cultivated land risk are also diversified, and carbon sequestration technology can effectively deal with greenhouse gas emissions, while reducing food waste and changing dietary habits have also become effective ways to reduce the risk of cultivated land. The development of planetary boundary framework (Rockström et al., 2009) has shifted the study of cultivated land risk from elemental to systemic research, and scholars at home and abroad have gained a deep understanding and explored the coupled nonlinear relationship between cultivated land use system and elements.

4.2 Application of planetary boundary framework in cultivated land risk studies

Since the industrial revolution, human activities have become a major driver of global environmental change, and human activities can lead to an Earth system outside the stable environmental state of the Anthropocene, with threatening and even catastrophic

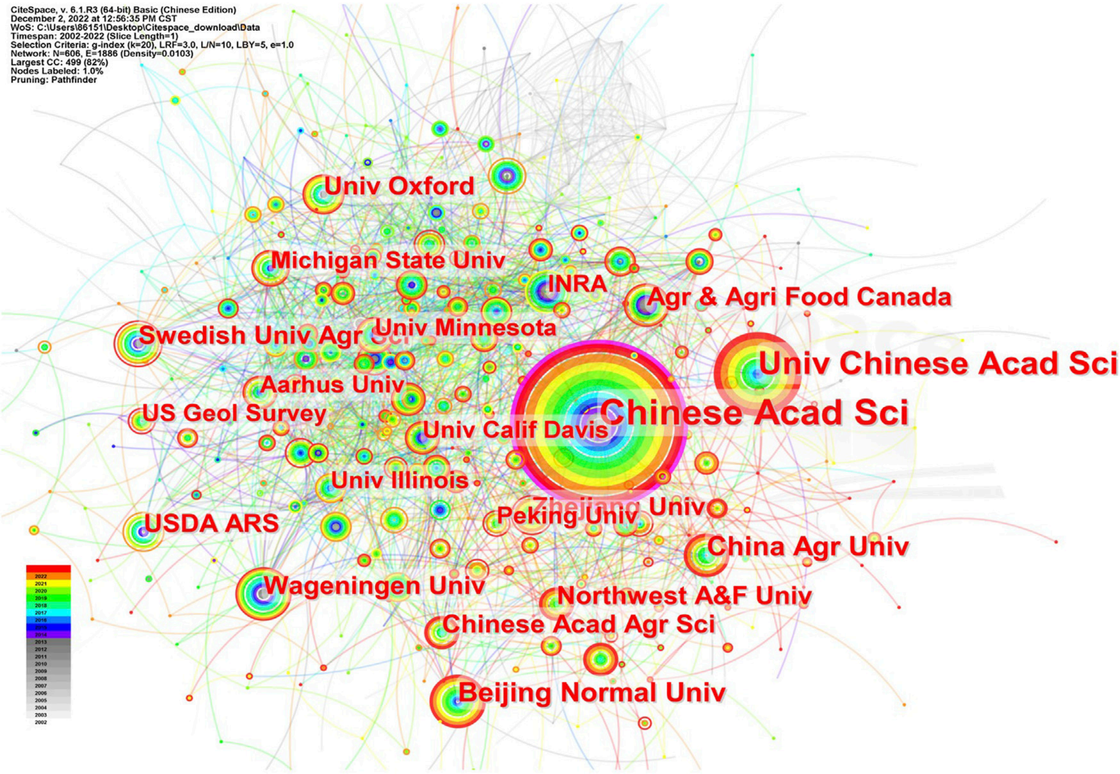

FIGURE 4
Institutional cooperation network map of cultivated land risk research.

consequences for much of the world (Crutzen, 2002; FU et al., 2006). To meet the challenge, the planetary boundary framework was formally proposed by Rockström et al. (2009), Center for Resilience Research, Stockholm University, Sweden, and has elicited a strong response from scientists worldwide (Dearing et al., 2014; Mace et al., 2014). The framework focuses on key biophysical processes of the Earth, which have evolved and now identify nine processes such as climate change, biosphere integrity, stratospheric ozone depletion, ocean acidification, biogeochemical flows (nitrogen and phosphorus cycles), land system changes, freshwater use, atmospheric aerosol loading, and the introduction of new entities (Steffen et al., 2015), defining the relative boundaries for human operations and security within which humans can safely operate in relation to the Earth system. The framework argues that these boundaries, if crossed, have a high potential to trigger irreversible nonlinear changes in the state of the Earth system, with consequent adverse effects on human wellbeing. This provides an important methodological reference for quantifying the magnitude of the impact of external risks on cultivated land.

The planetary boundary framework is based on the theory of homeostasis and mutation of complex systems and is centered on maintaining the stability of the Earth's ecosystem for human wellbeing. To maintain system homeostasis, the stable resource and environmental conditions during the Holocene geological period before the industrial revolution are used as a reference to analyze the variables of the Earth's key biophysical processes, determine the critical thresholds of the variables, and provide early warnings based on the critical thresholds to ensure that changes in the system state receive early attention and preventive measures are taken. The planetary boundaries represent a relatively conservative estimate of critical thresholds, which are positioned at the lower end of the uncertainty range. The current threshold interval of planetary boundaries consists of three parts: first, the safe operating space, in which human activities have basically no impact on the stability of the Earth system; second, the uncertainty region, which has exceeded the planetary boundaries, is the region where the risks to the Earth system beyond this region have not yet been quantified and cannot be analyzed; third, in the high-risk region, human activities significantly exceed planetary boundaries and may cause irreversible effects on the Earth system environment (Figure 5A).

Currently, Rockström et al. (2009) and Steffen et al. (2015) have proposed and refined the planetary boundary framework, offering the possibility to study the effects of different subjects on the Earth system at the global scale. Newbold et al. (2016) explored the impact of land use and related stressors on local biodiversity based on the planetary boundary framework, quantifying the extent of biodiversity destruction due to the effects of cultivated land use and beyond the safe boundary of the environment. Springmann et al. (2018) applied the framework to food production systems and analyzed the safety boundaries of climate change, land use system changes, freshwater use, and nitrogen and phosphorus loss in biogeochemical flows in food production systems. Lade et al. (2020) based on the planetary boundary framework, argued that there are interlinked relationships among planetary boundaries, i.e., planetary boundaries affect each other and interact with each

TABLE 4 Global research on the topic of cultivated land risks, including risk types, causes and control strategies.

Methods	Area	Types of cultivated land risks	Causes of cultivated land risks	Management strategy	Source	Referencces
Data analysis	World	Wildlife habitat loss	Agricultural intensification	Sustainable intensification (closing the yield gap)	Science	Mueller et al. (2012)
Data analysis	World	Species diversity loss	Agricultural intensification	High-yield farming	Science	Green et al. (2005)
Geostatistical analysis land use investigation industrial composition analysis	X Town, Changshu City, Jiangsu Province, China	heavy metal pollution	Urbanization and Industrialization	——	Chemosphere	Jiang et al. (2017)
Modeling with large flows of goods, people and capital and linking local land use to factors on a global scale	China, Costa Rica, El Salvador, Vietnam	disturbed forests	Economic globalization	Land use zoning; Agricultural intensification	PNAS	Lambin and Meyfroidt (2011)
Literature Review	Region	decline in farmland biodiversity	Agricultural intensification	Cross-cutting policy frameworks and management solutions	Trends in Ecology and Evolution	Benton et al. (2003)
Positive Matrix Factorization (PMF) modeling	Lianyuan, Hunan Province, China	heavy metal pollution	Coal Mining	——	Environmental pollution	Liang et al. (2017)
Multivariate statistical analysis GIS-based geostatistical methods and Positive Matrix Factorization (PMF) receptor modeling	Northwest China	heavy metal pollution	Urbanization and Industrialization	——	Chemosphere	Guan et al. (2018)
Life Cycle Assessment (LCA)	World	Greenhouse gas emissions	Land use change	Extract biofuel from waste product	Science	Searchinger et al. (2008)
Data Analysis and Modeling	southwest Ghana and northern India	Species diversity loss	Expansion and Intensification	land sparing	Science	Phalan et al. (2011)
Data analysis	World	Species diversity loss	Human activities	——	Nature	Newbold et al. (2015)
Data analysis	World	Greenhouse gas emissions; Water consumption	Climate Change	Closing the yield gap; Reducing waste Changing diets; Expanding aquaculture	Science	Godfray et al. (2010)
Planetary boundaries	World	Greenhouse gas emissions; Water Scarcity; Species diversity loss; Nitrogen and phosphorus emissions exceed the standard	Human activities	——	Science	Steffen et al. (2015)
Data analysis	World	Soil degradation	Land use change	Carbon sequestration (judicious land use and recommended management practices (RMPs))	Science	Lal (2004)
Data analysis	World	Greenhouse gas emissions	Land reclamation	——	Nature	Tilman and Clark (2014)
Data analysis	World	Greenhouse gas emissions; Species diversity loss; Water consumption and pollution	Human activities	Halt agricultural expansion; Closing 'yield gaps' on underperforming lands; increasing cropping efficiency; shifting diets and reducing waste	Nature	Foley et al. (2011)

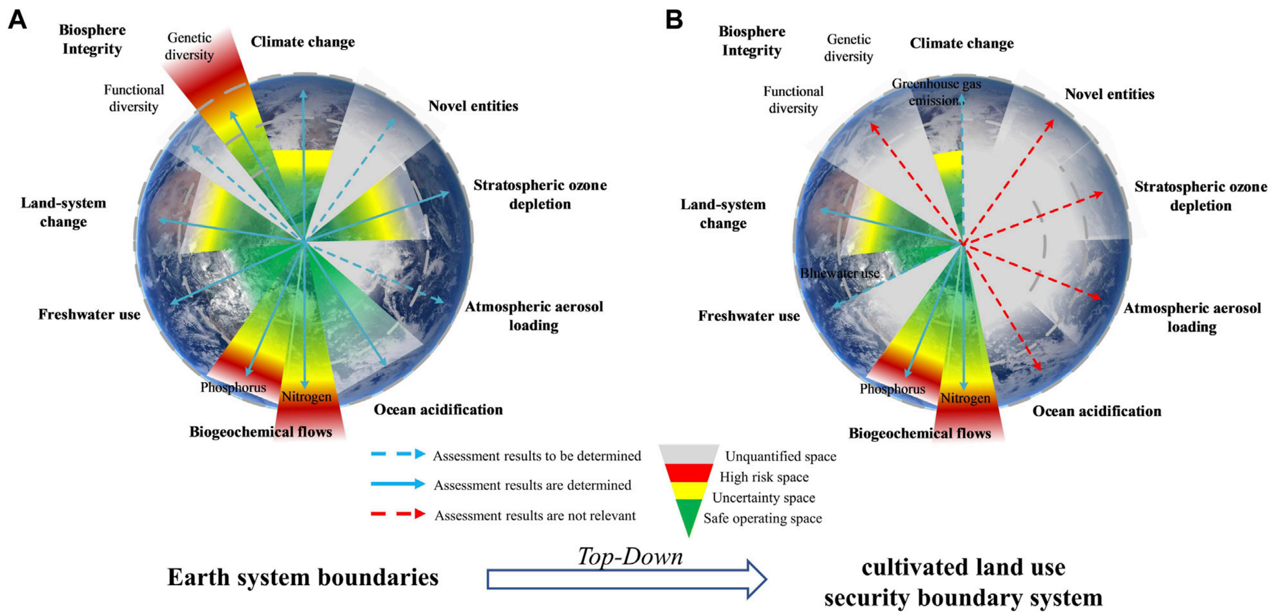

FIGURE 5
A cultivated land use security boundary system constructed based on the earth system boundaries framework.

other, and carefully analyzed the effects of land use changes on planetary boundaries such as nitrogen, phosphorus, water and greenhouse gases. Cultivated land use is an important component of land use, and changes in cultivated land use will also have significant effects on climate change, freshwater use, and nitrogen and phosphorus loss in biogeochemical flows.

In summary, the planetary boundary model allows for the multidimensional quantification of factors influencing cultivated land risk. Anchored in fundamental logical perspectives and coupled with downscaling methodologies, the global-scale model can be downscaled to encompass larger regions, nations, and even smaller scales. Drawing insights from the research achievements of relevant scholars (Rockström et al., 2009; Steffen et al., 2015; Hu et al., 2020; Lade et al., 2020), we comprehensively construct the planetary boundary framework (Figure 5B) for cultivated land use systems. This framework serves as a theoretical guide for future investigations into cultivated land risk, rooted deeply in the principles of planetary boundary theory. Looking ahead, we anticipate the significant theoretical guidance this comprehensive endeavor will offer to forthcoming risk assessments within cultivated land systems, grounded in the foundations of planetary boundary theory.

4.3 Experience of risk management strategies for cultivated land

In the 1960s, in order to solve the problem of severe soil erosion and massive soil erosion and to avoid environmental degradation caused by land use, the United States was the first to propose the Evaluation of Land Resource Production Potential, to classify land use potential, to classify eight soil potential classes according to soil, slope, erosion type and erosion intensity, and to develop a more complete soil map for soil and water conservation purposes (Klingebiel and Montgomery, 1961; Zhu, 1997). Best Management Practices (BMPs) were introduced in the 1970s in the United States, and the core of the BMPs is the use of a combination of measures to control agricultural pollution from cultivated land use, which has achieved good results (Bracmort et al., 2006; Reimer et al., 2012). A system of pesticide business license, pest control consultation, and restricted level pesticide application license has been established (Guo et al., 2015). The BMPs includes three levels of nutrient management practices, tillage management practices, and landscape management practices, and each state government has developed detailed rules and practices and formed corresponding testing and management agencies. In 1985, the U.S. Congress passed the “Food Safety and Security Act,” and the following year initiated a nationwide 10–15-year ecological restoration program for cultivated land (Wu et al., 2019). This program aimed to systematically remediate cultivated land with severe ecological issues. The U.S. government also introduced fallow and land protection programs to safeguard environmentally vulnerable lands and promote ecological restoration through fallowing (Sullivan et al., 2004; Stubbs, 2013). Additionally, a series of conservation programs were implemented, effectively preserving high-quality cultivated land (Jiang et al., 2019; Ke, 2001).

The EU has devised policies addressing environmental risks in agriculture, demonstrating a profound concern for the environmental condition of the agricultural sector (Dobbs and Pretty, 2008; Vannini et al., 2008), which define the two pillars of the EU agricultural policy, including subsidies for ecologically fragile areas to reduce the use of harmful fertilizers and pesticides, as well as subsidies for afforestation, and encouraging the development of multifunctional roles of agriculture. In 2003, the EU reformed its agricultural policy, with a focus on the introduction of the decoupled “Single Farm Payment” (SFP). In 2003, the EU reformed its agricultural policy, and one of the highlights of the reform was the introduction of the decoupled "Single Farm Payment" (SFP) (Fraser, 2003; Wang, 2009), where agricultural land use must meet a series of criteria related to soil conservation, soil organic matter maintenance, habitat avoidance and water management in order to receive agricultural subsidies. This provides a solid basis for agricultural land risk control in the EU. In order to effectively monitor the presence of soil erosion, soil ecological degradation, soil heavy metal contamination, soil compaction and soil salinization in each country, the Soil Environmental Assessment Health Project was introduced in the EU in 2007 (Kibblewhite et al., 2007). The project identified nine major threats affecting soil quality in Europe as soil erosion, declining organic matter content, soil pollution, soil compaction, soil salinization, declining biodiversity, soil sealing, landslides, and desertification. Based on their threat level, a minimum data set of 27 key issues and 27 monitoring indicators that can encompass all threats were finally selected to form the monitoring indicators. The EU's farm and soil environmental policy has, to a certain extent, effectively managed the environmental risks caused by the current agricultural production process and provided a guarantee for the sustainable development of EU agriculture.

The Japanese government attached great importance to agricultural land and arable land, and enacted many ordinances aimed at strengthening the management and protection of cultivated land. After the establishment of the peasant land ownership system in post-war Japan, a strict control policy on high-quality arable land was implemented, stipulating that all types of land could not be freely transferred. The rapid economic development of Japan in the 1960s and 1970s led to an increase in agricultural inputs, especially the extensive use of chemical fertilizers and pesticides. Consequently, this not only adversely affected the ecological environment but also had a negative impact on the quality of agricultural products (Qian et al., 2016). In 1992, the Ministry of Agriculture, Forestry and Fisheries of Japan passed the New Food/Agriculture/Rural Policy Act, which established the "Basic Policy for the Promotion of Environmentally Friendly Agriculture" to reduce the use of pesticides and chemical fertilizers by improving soil fertility and promoting organic farming and pesticide- and fertilizer-free cultivation to achieve sustainable agricultural production. The Basic Law for Food Agriculture and Rural Development, enacted in 1999, promotes environmentally friendly agriculture throughout the country, taking measures such as promoting the use of compost while reducing chemical fertilizers, promoting eco-farmer certification and giving interest-free loan support for agricultural improvement funds (Ma and Mao, 2019). In the 21st century, Japan has enacted policies and measures such as the Agricultural Environmental Code, the Organic Farming Promotion Act, and the Measures to Protect and Enhance Agricultural Land, Water, and the Environment, aiming to improve soil, reduce the intensity of chemical fertilizer and pesticide inputs, increase biodiversity, reduce environmental loads, achieve sustainable use of agricultural production, and ensure food safety.

The cultivated land risk control policies implemented in the United States, Japan, and Europe underscore several key recommendations for achieving sustainable development of cultivated land and mitigating associated risks. These recommendations can be summarized as follows.

(1) Rigorous Land Use Control: The first crucial recommendation involves the strict control of cultivated land, which includes prohibiting arbitrary changes in land use and giving priority to the protection of high-quality cultivated land.
(2) Enhancing Soil Fertility: The second recommendation centers on improving soil fertility. This entails the strict regulation of chemical fertilizers and pesticides use to reduce environmental impacts and prevent soil degradation.
(3) Regular Environmental Monitoring: The third recommendation underscores the importance of establishing regular environmental monitoring systems. This comprehensive network should be complemented by incentives for agricultural producers adopting eco-friendly practices.
(4) Positive International Impacts: Acknowledging the positive effects of the risk control policies of the United States, Japan, and Europe on cropland risk control worldwide.
(5) Global Research and Collaboration: The need for enhanced scientific research in cultivated land risk control, the development of unified and coordinated policies, the creation of risk control mechanisms and institutions, and the promotion of sustainable land resource management on a global scale is emphasized.

In summary, these recommendations emphasize the importance of taking proactive measures to protect cultivated land, improve soil quality, monitor environmental conditions, and glean valuable insights from successful international policies. This approach is aimed at promoting and ensuring sustainable land use practices worldwide.

4.4 Challenges and prospects for research on cultivated land risk

The sustainable use of cultivated land is crucial for supporting future food production. However, risks to cultivated land pose a significant challenge to achieving sustainable use. Therefore, it is essential to scientifically quantify the various risks and identify ways to prevent or manage them. However, due to the wide variety and partial difficulty in quantifying the types of risks, it is challenging to guide the sustainable use of cultivated land. The planetary boundary framework provides a good paradigm for quantifying the impact of each element on the Earth system. However, finding the boundaries of the Earth system related to cultivated land is an important issue for future research. Scholars have made efforts to quantify the relevant boundaries of cultivated land use, but the cultivated land system is a complex human-natural complex, and further research is needed to quantify the relevant boundaries and the inter-boundary relationships, scale effects, and driving mechanisms. Future studies can refer to the planetary boundary framework to explore the effects of changes in cultivated land use on planetary boundary indicators such as climate change, freshwater use, and nitrogen and phosphorus loss in biogeochemical flows. By applying this framework to the cultivated land utilization system, we can quantify the environmental risk thresholds in a scientific way and have control objectives in the regulation of the cultivated land utilization system, thus realizing the sustainable utilization of cultivated land resources.

The implementation of cultivated land risk control mainly involves two mechanisms: the government mechanism and the social mechanism. The government mechanism plays a leading and supervisory role in risk management, while the social mechanism involves the owners and direct users of the cultivated land use system. To achieve effective cultivated land risk management, it is necessary to guide these two mechanisms to work together and build a main system of cultivated land risk management. Furthermore, there is a need for debate and discussion to develop pathways for sustainable cultivated land risk research and utilization. The objectives of cultivated land risk research in the new era should focus on transformative ecological governance, which involves stakeholder and institutional changes and methodological changes to proactively improve the degraded cultivated land use system. This will build a system of cultivated land risk research with multi-interest synergy, multiple resource integration, and full-cycle regulation to ensure social response matches the changing cultivated land use system. This will narrow the sustainable development gap of the cultivated land use system and regulate it back to a safe operating space, thus realizing the sustainable use of cultivated land resources and fair and just human social development.

Author contributions

Data curation: ZZ, ML, LW, and EX; formal analysis: ZZ, ML, and LW; methodology: ZZ, ML, LW, EX, and XK; writing—original draft: ZZ and ML; writing—review and editing: ZZ, ML, LW, EX, and XK. All authors contributed to the article and approved the submitted version.

Funding

This work was supported by the Chinese Social Science Foundation (19ZDA096), the Chinese National Natural Science Foundation (42171289 and 42201285). China Postdoctoral Science Foundation (2023M733781); Ministry of Science and Technology of the People's Republic of China (2021FY100403).

Conflict of interest

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frontiers | Frontiers in Environmental Science

TYPE Original Research
PUBLISHED 05 December 2023
DOI 10.3389/fenvs.2023.1124637

OPEN ACCESS

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RECEIVED 15 December 2022
ACCEPTED 10 November 2023
PUBLISHED 05 December 2023

CITATION
Faye B, Du G, Li Q, Sané T, Mbaye E and Zhang R (2023), Understanding the characteristics of agricultural land transition in Thiès region, Senegal: an integrated analysis combining remote sensing and survey data.
Front. Environ. Sci. 11:1124637.
doi: 10.3389/fenvs.2023.1124637

Understanding the characteristics of agricultural land transition in Thiès region, Senegal: an integrated analysis combining remote sensing and survey data

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Adopting an integrated analysis is a prominent tool for a coherent understanding of the characteristics of agricultural land transition in developing countries. Hence, using an integrated analysis combining remote sensing and survey data, this investigation aimed to understand the spatial-temporal distribution and intensity of agricultural land transition in Senegal through a case study in the Thiès region. Through ArcGIS and ENVI software, we interpreted the land use types from 2000 to 2020 and the transfer matrix method used to characterize the agricultural land transition. Then, the Pearson correlation coefficient is used to determine the intercorrelation between natural and socio-economic driving factors of agricultural land use. The main results show that agricultural land transition was about −588.66 km^2. Grassland was the most crucial land morphology to participate in this transition. Regarding spatial distribution, the highest net transition of agricultural land was recorded in Mont-Rolland (33.22%) and the lowest in Sandiara commune (−41.73%). The temporal distribution is represented in Koul, with −0.35%, and Mont-Rolland commune, with 24.84%. The intensity of agricultural land transition was high in Malicounda commune, at 11.34%. The social survey also shows a strong relationship between wind erosion and land salinity (0.971) as potential driving factors that may induce agricultural land transition. Based on an integrated method, the contribution of this study enhances the theoretical approach and methodology for assessing the mean potential driving factors in developing countries such as Senegal. Consequently, agricultural land transition in Thiès region was complex and must be implemented with complex and comprehensible policy solutions.

KEYWORDS

Thiès-Senegal, agricultural land transition, integrated analysis, spatiotemporal distribution, social survey

Introduction

Agricultural land transition has become an important component of the environmental risks that require immediate and long-term solutions. Many researchers have studied the changes in agricultural land use due to socio-economic development (Shi Ge, 2018; Zhou et al., 2021). In early 1970, a few scholars highlighted that agricultural land is fundamental to human survival and economic development (Bell and Borgstrom, 1966). Hence, it is implied that agricultural land use and socio-economic development have gone hand in hand for a long time. What's more, many driving factors increasingly threaten agricultural land, such as the need for land for housing (Faye, Du and Zhang, 2022), urbanization (Lyu et al., 2021), socio-economic development (Niu Bo et al., 2021) and so on. Conversely, agricultural production and economic growth depend on land availability, which has a dual relationship. From then on, a comprehensible analysis of agricultural land transition is a prerequisite to optimal utilization (Amara et al., 2021).

For this reason, among various research trends, coordinating socio-economic development, which needs land and agricultural land area for production, has recently raised huge concerns worldwide. In other words, agricultural land decline or transition is central to scientific research papers addressing food security. So, governments and scientific researchers are increasingly interested in the potential factors influencing the agricultural land transition. As an ecosystem service value, agricultural land provides multiple and diverse contributions to socio-economic development. Or, ecosystem service value is indispensable when balancing the need for food production and ecological protection because it can clarify a region's environmental assets and values (Li et al., 2022).

However, the process of agricultural land transition is often non-linear and may revolve around two interrelated questions: the physical environment and socio-economic driving factors (Paul and Rashid, 2017; Ustaoglu and Williams, 2017; Faye and Du, 2021), and it is associated with other societal and biophysical system changes (Lambin and Meyfroidt, 2010). In that situation, the intensity of land use is directly related to how land is used, especially agricultural land (Sang et al., 2019). Relevant studies point out that increasing food demands are causing rapid changes in farming systems, often involving intensified land use (Kuchimanchi et al., 2021). Simultaneously, many developing countries have policies to transition from subsistence farming into market-oriented approaches in response to the increased demand for animal-source food (Kuchimanchi et al., 2021), and the need for crop production is increasing globally (Awoonor et al., 2021). As a result, both situations have the potential to stimulate new land use while also reshaping agricultural land morphology. This situation was observed in Ivory Coast, whose agricultural land extension caused the diminished forest land area (Kouassi et al., 2021). Therefore, this change in agricultural land use can critically impact environmental resources, biodiversity, and, eventually, human wellbeing. Along with the above issue, other studies suggest that converting grassland, wetlands, and forests to croplands may contribute to environmental degradation and diminished ecosystem sustainability (Joshi et al., 2019). So, the connection between ecological risk and agricultural land changes could hurt the agricultural land's fertility. In the statement, guaranteeing food security and conserving agricultural land size qualitatively while preserving the environment are global concerns.

In addition to these issues, population growth can threaten agricultural land morphology. By 2100, the world's population is projected to reach approximately 10.9 billion, with annual growth of less than 0.1% (Anthony Cilluffo, 2019). This estimate is comparable to our study area (Thiès region), which had approximately 1,788,864 inhabitants in 2013, with a projected 2,464,554 inhabitants by 2025, according to the National Agency for Statistics and Demography of Senegal (ANSD). Along with this projection, due to economic policies that may increase income, developing countries are expanding their economies and urbanizing their populations, which could endanger the environment (Pachiyappan et al., 2022) and threaten the availability of agricultural land. In this context, the process of agricultural land transition may be critical due to the need for a new land area for developing economic growth. For example, in Northeast China from 2000 to 2020, 81.6% of the land occupied by the expansion of rural settlements came from cultivated land (Wang et al., 2022). Therefore, socio-economic and population growth influence agricultural land availability, as is evident. In addition, we can see population migration from rural to urban areas in COVID-19, which may contribute to the emergence of additional suburban towns (Faye, Du and Zhang, 2022), threatening agricultural land in the peri-urban zone. So, compared with industrial countries, over the past century, agricultural land use in the United States has seen drastic shifts to support the increasing demand for food and commodities (Spangler Kaitlyn, 2020). Throughout this context, we assume that the unplanned expansion of built-up areas toward peri-urban cities has accelerated agricultural land transition, leading to farmland losses (Erasu Tufa Duguma, 2022). The rapid development of agriculture is inseparable from the strong support of finance (Yang et al., 2022). Or the lack of finance for agriculture may induce land abandonment. In this case, land abandonment has positive and negative consequences on the landscape's abiotic and biotic components (Subedi, Kristiansen and Cacho, 2022). Consequently, understanding the characteristics of agricultural land transition is becoming more complex. In other words, agricultural land management became a crucial challenge in Senegal.

Accordingly, urbanization is another major social, economic, and demographic trend with consequences for the structure and function of agricultural landscapes (Vanbergen Adam J, 2020). For this reason, implementing new agricultural land policies and economic development in coordination with natural and socio-cultural factors may go hand in hand. However, it should be clear that research on agricultural land use would help stakeholders make better agricultural resource decisions. Because of the importance of agricultural land, certain governments develop more cutting-edge research policies for managing agricultural land to achieve this goal. For instance, the governments of Russia (Chigvintsev Victor, 2020) and Australia (Naudiyal Pratibha, 2021) implemented a new approach to technical, economic, and agricultural development policies to ensure food security and protect agricultural land. In Senegal, the primary land use policies have not been significantly reformed since 1960 (Niang, 2017). However, the main question is how agricultural land transition can be accomplished in Senegal without significant land policy reform.

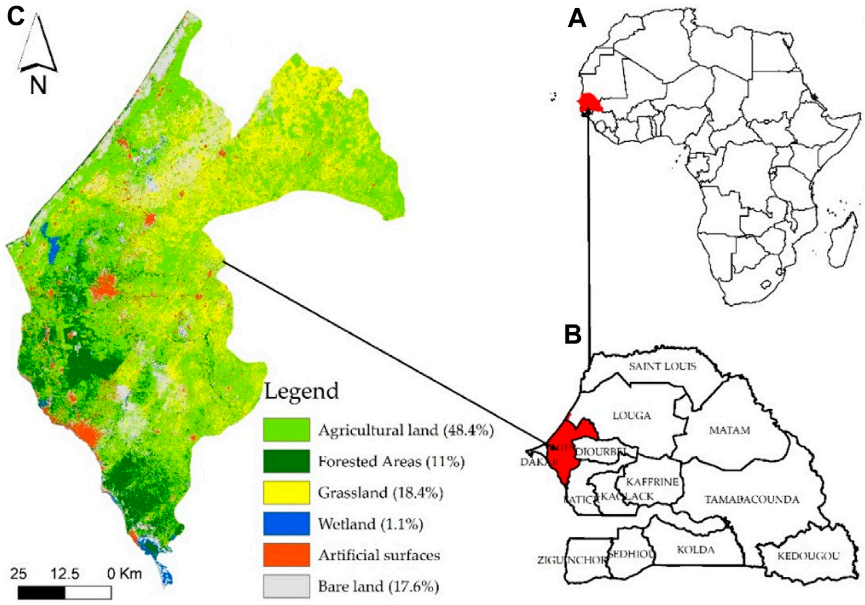

FIGURE 1
The localization of the study area, **(A)** African continent, **(B)** Senegal country, and **(C)** Thiès region.

What is the potential influence of public policy on agricultural land transition? Are agricultural land's initial and subsequent driving factors sufficient to comprehend without the farmer's perception of agricultural land transition? Which new research methods can be implemented to make Senegal's agricultural land transition process apprehensible? As a result, the research trend shows that GIS technology provides a flexible tool for spatial and statistical analyses coupled with modelling (Rozario et al., 2017). So, the combination of spatial statistics provided by remote sensing images and survey data may significantly impact the comprehensive understanding of the process of agricultural land transition in Senegal, in particular in the Thiès region. There is, however, a paucity of studies evaluating the characteristics of agricultural land transition with an integrated method. In that sense, this study is significant because it can contribute to and state farmers' perceptions about the causes of agricultural land transition while also highlighting policy shortcomings that may induce a rapid agricultural land transition. In another sense, this investigation was critical because we expected it to stimulate research on sustainable agricultural land management systems that can directly contribute to national food security policies and improve Senegal's land use information.

Following this ascertainment, this article provides a new approach and methodology for comprehensively understanding Senegal's agricultural land transition process. From then on, through an integrated analysis using remote sensing and social survey data, this investigation aims to understand the spatial-temporal transition of agricultural land in Senegal through a case study in the Thiès region from 2000 to 2020. Our specific objectives are: 1) to quantify agricultural land use transition; 2) to analyze the spatial and temporal distribution of agricultural land transition and its intensity; and 3), through the simple regression analysis model, to assess the farmer's perception regarding the influencing potentials and driving factors of agricultural land transition. So, the present study may provide significant insights into understanding the dynamic evolution of agricultural land in Senegal.

Overview of the study area

The spatial extent of Thiès region is between 10° 44′ 46″and 10° 52′ 46″north latitude and 78° 39′ 11″and 78° 44′ 13″west longitude. Thiès region was once an agricultural country where agriculture, especially groundnuts and vegetables, became essential to Senegal's economy. Regarding land area, it is one of the smallest regions in Senegal, at about 6669.6 km^2 or 3.35% of the total area of Senegal. As shown in Figure 1-b, it is bounded to the North by the Louga region, south by the Fatick region, west by the Atlantic Ocean and Dakar region (the capital of Senegal), and to the east by the Diourbel and Fatick regions. The Thiès region had 2,162,831 inhabitants in 2020, according to ANSD.

From the perspective of the agricultural situation, the main crop types are peanut, maize, millet, sorghum, and cowpea. According to the agricultural data collected in ANSD (accessed on 22 October 2022, at https://senegal.opendataforafrica.org/gallery?tag=DAPSA), the sown land area of these main crop types listed above represented about 266,668.24 hectors in 2020. In the same period, the agricultural production of these crops was around 25,3784.08 tons. From the point of view of spatial land use morphology, the remote sensing image analysis in 2020 shows that agricultural land use (48.4%) and grassland land (18.4%) represented the most significant land area dominant morphology, accounting for 66.8% of the total. Similarly, artificial surfaces represented 3.5% of the region's land area. Then, in this region, the topography is flat except for the

TABLE 1 Satellite images gathered for this research and their information.

Year	Acquisition date	Image Types	WRS Path/Row	Proportion of cloud%	Collected date
2000	11-November	Landsat7 ETM + C1	205/50	1	31 August 2022
	11-November	Landsat7 ETM + C1	205/49	7	31 August 2022
2005	17-September	Landsat7 ETM + C1	205/50	1	28 July 2022
	17-September	Landsat7 ETM + C1	205/49	5	28 July 2022
2010	25-October	Landsat 5 TM C1	205/50	0	28 July 2022
	25-October	Landsat 5 TM C1	205/49	6	28 July 2022
2015	24-Novomber	Landsat8 OLI	205/50	0.02	21 August 2022
	24-November	Landsat8 OLI	205/49	3.56	21 August 2022
2020	20-October	Landsat8 OLI	205/50	1.94	22 August 2022
	20-October	Landsat8 OLI	205/49	1.35	22 August 2022

"Plateau of Thiès," which culminates at 105 m of altitude. The temperatures are generally high, and the annual temperature cycle is complex. The maximum temperature is 33.2°. In addition, the interannual evolution of rainfall shows that the average rainfall was about 461.65 mm from 2000 to 2020, according to the data collected by the National Agency of Civil Aviation and Meteorology (ANACIM). The soil's characteristics were ferruginous tropical sandy soils that are slightly leached (Tappan et al., 2004).

Material and method

Data sources

Remote sensing data

The shapefile data corresponding to the limit of the administrative communes was collected from the Ecological Monitoring Centre (CSE) in Senegal. However, to achieve the research's aim, this paper takes all 31 administrative communes to analyze the spatial-temporal evolution of agricultural land transition and its characteristics from 2000 to 2020. The remote sensing data came from various satellites, including Landsat7 ETM + C1, Landsat5, and Landsat8 OLI (Table 1). All the remote sensing images were obtained from the United States Geological Survey (USGS) website with a spatial resolution of 30 m (http://earthexplorer.usgs.gov/).

The collection period of remote sensing images is essential to determining agricultural land accurately. Indeed, Senegal has two main seasons that mark the climatic regime: a dry season from November to April–May and a rainy season from May–June to October, depending on the geographical location (Ecological Monitoring Centre, 2018). Thiès region is one part of the ground basin in Senegal, where the wintering extends from June to October (Sagna Pascal, 2015), coinciding with our study area's rainy season. However, to maximize the characteristics of agricultural land, we chose the winter months to minimize the effects of clouds and seasonal variation. Therefore, according to Feteri et al., the selection of Landsat images was mainly based on availability, cloud cover percentage, and correspondence (Teferi et al., 2013). Due to these constraints, the Landsat images were collected between September and November.

Social survey data and variables explanation

A comprehensive questionnaire for a social survey was designed to collect information about the potential factors affecting the agricultural land transition from the farmers in 11 administrative communes in the Thiès region (Figure 2). In total, 600 questionnaires were collected in October 2022. In addition to this social survey, a field interview was conducted with the commune administrators. Globally, the survey questionnaire was composed of four sections. Only the third section relates to farmers' perceptions of the agricultural land transition's potential driving factors, which this paper explores.

Identifying major underlying factors of agricultural land use transition is essential for developing countries to meet a comprehensive land structure and management. The African continent is growing in importance with climate change and population pressure on land (Home, 2021). As a result, the complex driving factors of agricultural land transition, such as socio-economic (Xian, Li and Qi, 2019) and natural environment (Long et al., 2021) will be used as a reference to evaluate the main agricultural land transition factors. The social and economic variables selected include 1) population growth and 2) urban expansion. In addition, we assume that (3) a lack of investment in agriculture, 4) a suitable land policy, and 5) a high land price may facilitate the agricultural land transition. For this reason, these variables were added to the socio-economic variables to make the research more understandable.

Prior work has highlighted that precipitation (rain, snow, etc.) and temperature determine the potential distribution of terrestrial vegetation and constitute the principal factors in the genesis and evolution of soil (World Meteorological Organization, 2005). The study area has a climate difference in rainfall (Faye et al., 2018). The average rainfall is the main factor for agricultural production and determines the evolution of the sown land area (FAYE Bonoua, 2016). So, our investigation considers 6) rainfall variability and 7) temperature as the main factors affecting the agricultural land use transition. In addition, 8) deforestation, 9) soil salinization, and (10) wind and (11) hydric erosion were also significant variables given

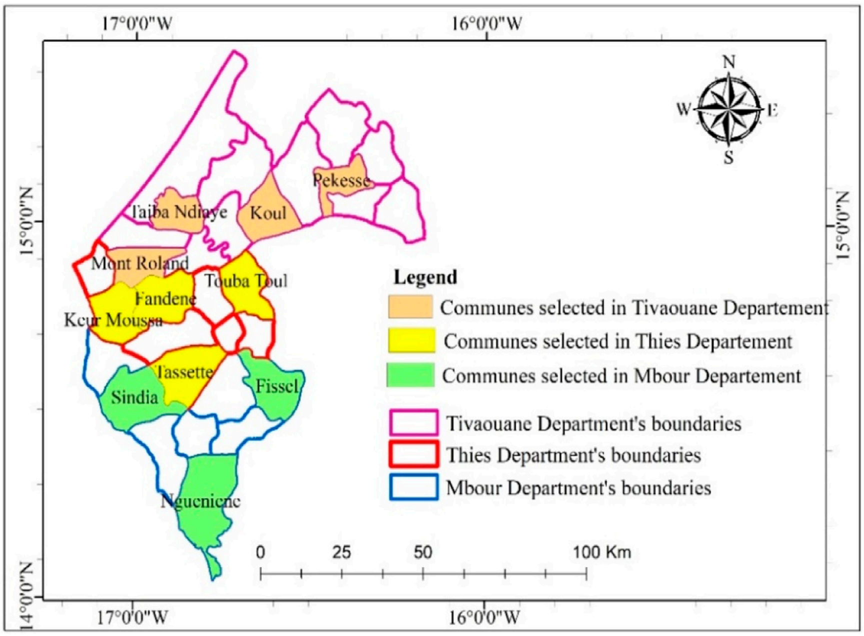

FIGURE 2
The sampling strategy of the social survey in Thiès region, October 2022.

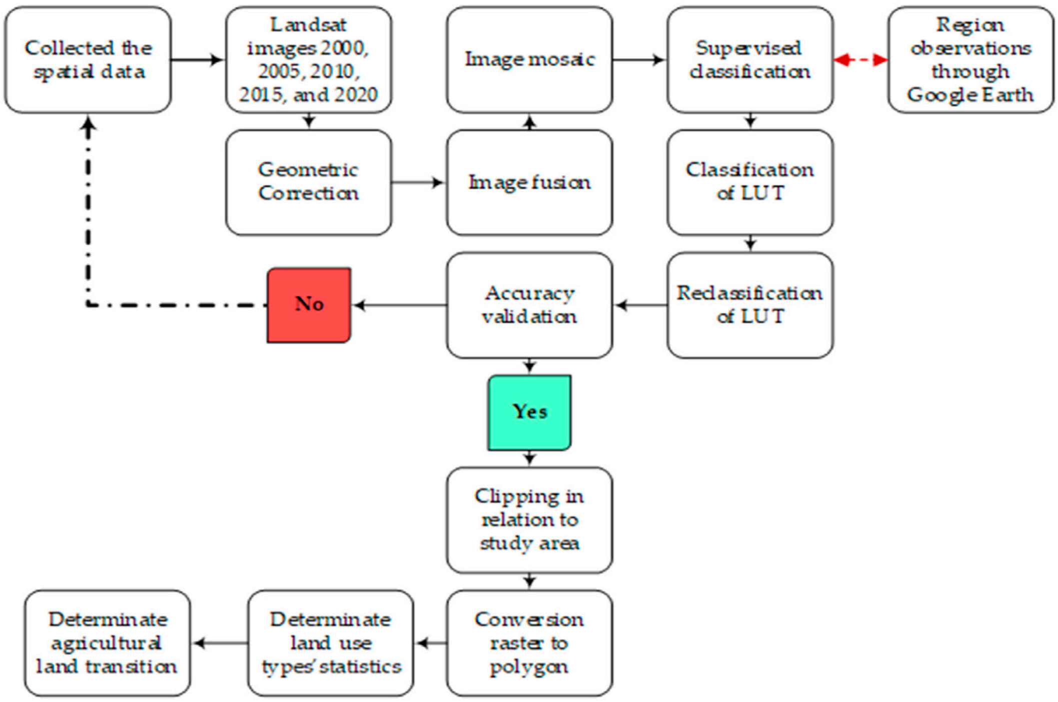

FIGURE 3
The workflow chart of remote sensing image processing.

the topography and forested areas in the study area. Given the complexity of socio-economic development and the natural environment in the Thiès region, 11 variables were selected for this investigation. The CommCare HQ software was used as a tool for collecting data. The face-to-face method was adopted by paying attention to ethical considerations such as sensitive responses like agricultural income. Additionally, the data screening process shows that 15 questionnaires were discarded due to a lack of logic. For this

TABLE 2 Classification method of land use categories.

N	Level I	Level II	Code
1	Agricultural land	Permanent crops; permanent pasture; agro-business landetc.	AL
2	Forested areas	Classified forests, casuarina, nature reserves, mangroves, open forests	FA
3	Grassland	Sparse grass, moderate and dense grassland	GL
4	Wetland	Lakes; permanent water and no permanent water; bottom land, reservoirs, and pond	WL
5	Artificial surfaces	Urban and built-up areas; rural settlements; photovoltaic power generation land; transportation facilities	AS
6	Bare land	Sandy land; ancient mining and quarrying areas; soil salinity; bare land; other lands that are not used until the mapping time)	BL

reason, 585 completed questionnaires were used in the following analysis.

Methods

Given the study area's size, two Landsat images were collected yearly. However, due to the characteristics of the remote sensing data, pre-processing is necessary to have more clarity. Therefore, several steps have been taken, as shown in Figure 3. First, to optimize the quality of the images, the layers were re-projected according to the reference projection system of the study area, which is World Geodetic System (WGS)_1984_Complex_UTM_Zone_28N (EPSG: 31028). This projection allows us to obtain expected results between the processed images. Then, we resampled the remote sensing images to 50 m, the standard resolution for all images (Díaz P. J, 2018). Second, after this geometric correction, such as atmospheric correction, gap fill in Landsat 7 ETM, and image mosaicking through ENVI software. In addition, the supervised classification is chosen for this study, and training samples are selected for each land cover class. Human-computer interaction interpretation methods extracted land use information from the remote sensing image data.

From then on, it is important to note that land use classification systems vary with the purpose and context of their use (Briassoulis, 2020). Consequently, using the classification system of Anderson JR et al. as a reference (Anderson James, 1976), we have reclassified the land use types into six (06) categories: agricultural land, forested areas, grassland, wetland, artificial surfaces, and bare land (Table 2). Additionally, as shown in Figure 3, it is essential to highlight that, during the classification of land use types, Google Earth played a significant role in identifying the unclear characteristics of certain land use morphologies. In addition, the remote sensing images were cut according to the size of the study area. Finally, after the raster conversion to polygons, we used the ArcGIS 10.6 platform to determine land use types' statistics and quantify the agricultural land transition for different periods.

An accurate assessment is essential for processing land use change analysis and classification (Islami et al., 2022). However, the overall accuracy values based on the post-classified images generated for 2000, 2005, 2010, 2015, and 2020 differed yearly. For instance, the least accurate year is 2020, with 0.91. The most significant record is 0.924, which was set in 2005. However, the overall accuracy for our study period was 0.93. Additionally, the kappa coefficient was about 89.05%, indicating that the simulation results have high consistency and accuracy with the actual LULC distribution (Pontius et al., 2008) because an overall standard accuracy for LULC classification is known to be between 85% (Anderson James, 1976).

Tracing sources and flow of agricultural land

Tracing the sources and flows of agricultural land can assist in determining how agricultural land is lost or gained from other types of land (transfer in or out) (Kumar Sathees, 2014). So, this process has followed many steps. Firstly, we introduced the land-use transition matrix to calculate land-use types' transition characteristics. The transition matrix reflects the transferred-out area at the initial period and the transferred-in area at the end period. The following equation was used to calculate the transition matrices:

$$Sij = \begin{vmatrix} S_{11} & S_{12} & S_{n21} \\ S_{21} & S_{22} & S_{n22} \\ S_{n1} & S_{n2} & S_{nn} \end{vmatrix} \quad (1)$$

where n represents the land use type before and after the transfer; i, j (i, j 1, 2. . ., n) represents land use type before and after the transfer, respectively; Sij represents the land use area i land type before transition to type j land type after transition.

Secondly, use the transfer matrix to determine the agricultural land amount and the net transition area transfer. Then, based on the above steps, the amount of "transition reduction" or "transition gain" in the net transition area of agricultural land types in different periods was calculated according to the equations above. The specific formula is as follows:

$$AL_{loss\ (i),j=}\frac{AL_{i,j}}{\Delta AL_I}\ X\ 100\, i \neq j,;\ AL_{gain\ (i),j=}\frac{AL_{i,j}}{\Delta AL_I}\ X\ 100\, i \neq j, \quad (2)$$

$$ALN_{loss\ (i),j=}\left(AL_{j,i} - AL_{i,j}\right)\Big/\left(AL_i - AL_i\right)x\,100\, i \neq j, \quad (3)$$

Where $ALloss_{(i),j}$ is the ratio of areas converted from agricultural land to land use type j $AL_{(i),j}$ to the total areas of all types of land converted from agricultural land in the year i (ΔALi). $ALgain_{(i),j}$ is the ratio of areas of land use type i converted to agricultural land (ALi,j) to the total areas of all types of land converted to agricultural land in year j (ΔALj). Here j refers to the column number, and i refers to the line number in the land transition matrix. Both $ALloss_{(i),j}$ and $ALgain_{(i),j}$ are contribution rates of land use of certain types converted to out of or to agricultural land. $ALNloss_{(i),j}$ refers to the net transition rate of agricultural land contributed by land use type j, calculated as the ratio of the net converted area from land use type j to agricultural land $(ALj,i - ALi,j)$ to the total net converted land areas to agricultural land in the year i $(AL.i - ALi.)$ (Li et al., 2021).

Analysis of agricultural land transition's temporal evolution

The temporal evolution of the dynamic index of land use change was expressed to measure the rapidity of land use transition (Hossein Talebi Khiavi, 2021). It refers to the rate at which specific land use changes over time (Du Guoming, 2018). So, the following Eq 4 was used in this study to show the rate of change (increase or decrease) of a type of agricultural land use over the study period.

$$V = \frac{Sb - Sa}{Sa} x \frac{1}{T} x100 \tag{4}$$

Where V was the evolution speed of agricultural land use types during the study period, Sa was the land area at the beginning of the study period; Sb was the land area at the end of the study period, and T was the time interval of the study years.

Analysis of agricultural land transition's spatial evolution

The spatial evolution of land use change is frequently characterized by amplitude. In this study, the amplitude of agricultural land net transition evolution was mainly characterized by the value of change in the quantitative transition of agricultural land. It was measured according to the land area of each commune. The equation below 5) determines the spatial index of agricultural land use change (Mohamed and Worku, 2019).

Additionally, several methods have been applied to understand the intensity of agricultural land transitions (Xian, Li and Qi, 2019). Hence, for a comprehensive understanding of the intensity of agricultural land transition, this study chooses the scenario of net transition of artificial surfaces for measuring the intensity of agricultural land transition according to the total size of each commune. This choice is justified by urbanization's continuous loss of agricultural land (Beckers et al., 2020). In other words, the irreversible farmland transition to built-up land occurs globally (Skog and Bjørkhaug, 2020). So, to accomplish this investigation, Eq 5 was also used to describe this intensity.

$$B_{it+n} = \left[\frac{(U_{it+n} - U_{it})}{T} * 100 \right] \tag{5}$$

Where: $Bi\ t + n$ is the annual expansion intensity of spatial unit i; $Uit + n$ is land use types area at the spatial unit i at time $t + n$; Ui t is land use area at the spatial unit i at time t, and T is the land area of at the spatial unit i.

Measuring the degree of spatial balance or imbalance of agricultural land transition

The equilibrium degree of transition is an index to characterize the equilibrium degree of agricultural land use following a change among regions. Several methods exist to appreciate the equilibrium distribution of two or many variables. The simple linear regression model was used in this study to assess the degree of balance or imbalance in agricultural land transition. The horizontal axis *(X)* represents the cumulative percentage of agricultural land net transition, and the vertical axis *(Y)* represents the cumulative percentage of communes.

$$y_i = B_i x_i + \epsilon_1 \tag{6}$$

where yi is an unobservable variable, $\boldsymbol{x}\ i$ is a vector of independent variables, $\boldsymbol{\beta}\ i$ is an array of parameters to be estimated, and εi is the random error term assumed to be distributed as a standard normal. The index denotes the ith household (Vixathep S, 2013).

In addition to the simple linear regression model, the coefficient of variation *(CV)* was calculated to appreciate the dispersion of agricultural land net transitions from one period to another. It is a statistical measure of how far apart the points in a data set are from the mean.

$$CV_{ij} = \frac{SD_{\cdot ij}}{NM_{\cdot ij}} \tag{7}$$

Where $CVij$ represents the value of agricultural land use transition to other land use types in county i during period j, where SD is the standard deviation of the data sample, MN is the average value of the data sample values of the CV related to whether and how to balance the set of results is spatially distributed.

Assessment of the farmer's perception of the drivers' factors of agricultural land transition

In this study, to understand the drivers' factors of agricultural land transition, the variables ranged from "strongly agree," "agree," "neutral," "disagree," and strongly disagree." This study chooses only the frequency of "strongly agree" for assessing the driving factors. Relevant studies target the social, economic, and natural factors that caused the agricultural land transition. This study used the method of intercorrelation between the variables to understand the phenomenon according to the farmer's perception. Hence, there are several methods of calculating correlation. The most common form, the Pearson product-moment correlation, was used in this study, as shown in Equation (8). As a result of the autocorrelation, it is possible to conduct a holistic evaluation and hierarchy of the factors and their order of importance in agricultural land transition.

$$r = \frac{n^* (\sum X, Y) - (\sum(x)^* \sum(y)))}{\sqrt{(n^* \sum(x^2) - \sum(x)2)^* (n^* \sum(y^2) - \sum(y)2)}} \tag{8}$$

Where r = correlation coefficient; n = the number of observations of the eleven communes selected for the social survey. The Pearson correlation coefficient ranges from *-1* to *+1*. When the coefficient = *0*, there is no linear correlation; when the coefficient = *+1*, there is a perfect positive linear correlation; and the coefficient = *-1*, there is a perfect negative linear correlation.

Results

Quantify the agricultural land use transition

The results presented in this section differed from one period to another (Table 3; Figure 4). Between 2000 and 2005, agricultural land use decreased by about $-303.01\ km^2$. During this period, forested areas ($168.55\ km^2$) were the most common land use type, resulting in the loss of agricultural land. Also, artificial surfaces accounted for $40.22\ km^2$ of this lost value. The situation remained similar in the second period (2005–2010) due

TABLE 3 Statistics of agricultural land net transition for 2000–2005, 2005–2010, 2010–2015, and 2015–2020.

Period	Land use types	Transfer in (Gain)	Transfer out (Loss)	Net Transition	Temporal index	Spatial index
2000–2005	Agricultural land	24.07	327.07	−303.01	−4.41	−4.54
	Artificial surfaces	53.19	12.96	40.22	14.77	0.60
	Forested areas	246.15	77.60	168.55	10.34	2.52
	Grassland	85.41	18.89	66.51	16.76	0.99
	Bare land	91.90	167.15	−75.25	−2.14	−1.12
	Wetland	117.81	14.83	102.98	33.06	1.54
2005–2010	Agricultural land	940.99	1214.2	−273.29	−1.07	−4.09
	Artificial surfaces	75.69	61.42	14.26	1.10	0.21
	Forested areas	403.00	668.72	−265.72	−1.89	−3.98
	Grassland	1214.01	460.07	753.94	7.80	11.30
	Bare land	521.30	628.68	−107.38	−0.813	−1.60
	Wetland	13.36	135.17	−121.81	−4.29	−1.82
2010–2015	Agricultural land	1017.63	1127.68	−110.05	−0.46	−1.65
	Artificial surfaces	93.81	42.56	51.24	5.73	0.76
	Forested areas	854.16	389.85	464.30	5.67	6.96
	Grassland	355.37	1263.04	−907.68	−3.42	−13.60
	Unused land	897.68	432.03	465.65	5.13	6.98
	Wetland	53.93	17.37	36.55	10.01	0.54
2015–2020	Agricultural land	1269.56	1149.99	119.56	0.50	1.79
	Artificial surfaces	112.14	68.92	43.22	2.98	0.64
	Forested areas	293.99	702.12	−408.13	−2.76	−6.11
	Grassland	845.14	442.01	403.12	4.34	6.04
	Bare land	677.50	792.98	−115.49	−0.69	−1.73
	Wetland	25.24	67.53	−42.29	−2.98	−0.63

to agricultural land losses of approximately −273.29 km^2; grassland was the primary contributor to the total loss. Compared with the two first periods, the agricultural land transition diminished from 2010 to 2015. The net transition of agricultural land was −110.05 km^2 or a difference of 193.05 km^2 compared to 2000–2005. Hence, the agricultural land net transition was intense from 2000 to 2005. Similarly, 2015–2020 shows that agricultural land was gained among the other land use types, with 119.56 km^2. As shown in Table 3, except for one period, this study's inter-period results revealed that the net transition of agricultural land was negative, whereas grassland gained the mean important flow.

The study period may produce noticeable results regarding agricultural land transition. This analysis shows the total net agricultural land transition was about −566.80 km^2. With 315.90 km^2, grassland represented the most significant flow. With 167.51 km^2, bare land came in second place. Artificial surfaces are the most common land use type that may threaten agricultural land, accounting for approximately 148.95 km^2. In summary, over the past 21 years, the most considerable change has been the substantial transition of agricultural land with a −1.667% temporal index, of which grassland has represented the most critical land use that caused this transition (Table 4).

Analyze the spatial distribution of net transition agricultural land

The spatial analyses of the net transition of agricultural land at an interval level, as shown in Figure 5, revealed several aspects. In fact, with a variation coefficient of −0.71%, agricultural land dropped in all the communes in the first period (2000–2005). The highest negative value of net conversion was recorded in the Mbayenne commune (−0.65%) and the least in the Noto G. Diama commune (−12.35%). In these communes, bare land gained about 6.14 km^2 in Noto G. Diama and 0.20 km^2 in Mbayenne. The coefficient variation was - 4.68 from 2005 to 2010, with Thieneba at −24.22% and Keur Moussa commune at 40.06% of the net transition of agricultural land. From 2005 to 2010, the average net transition of agricultural land was around −1.26 km^2, higher than the first period, which recorded −4.51 km^2. Then, the net

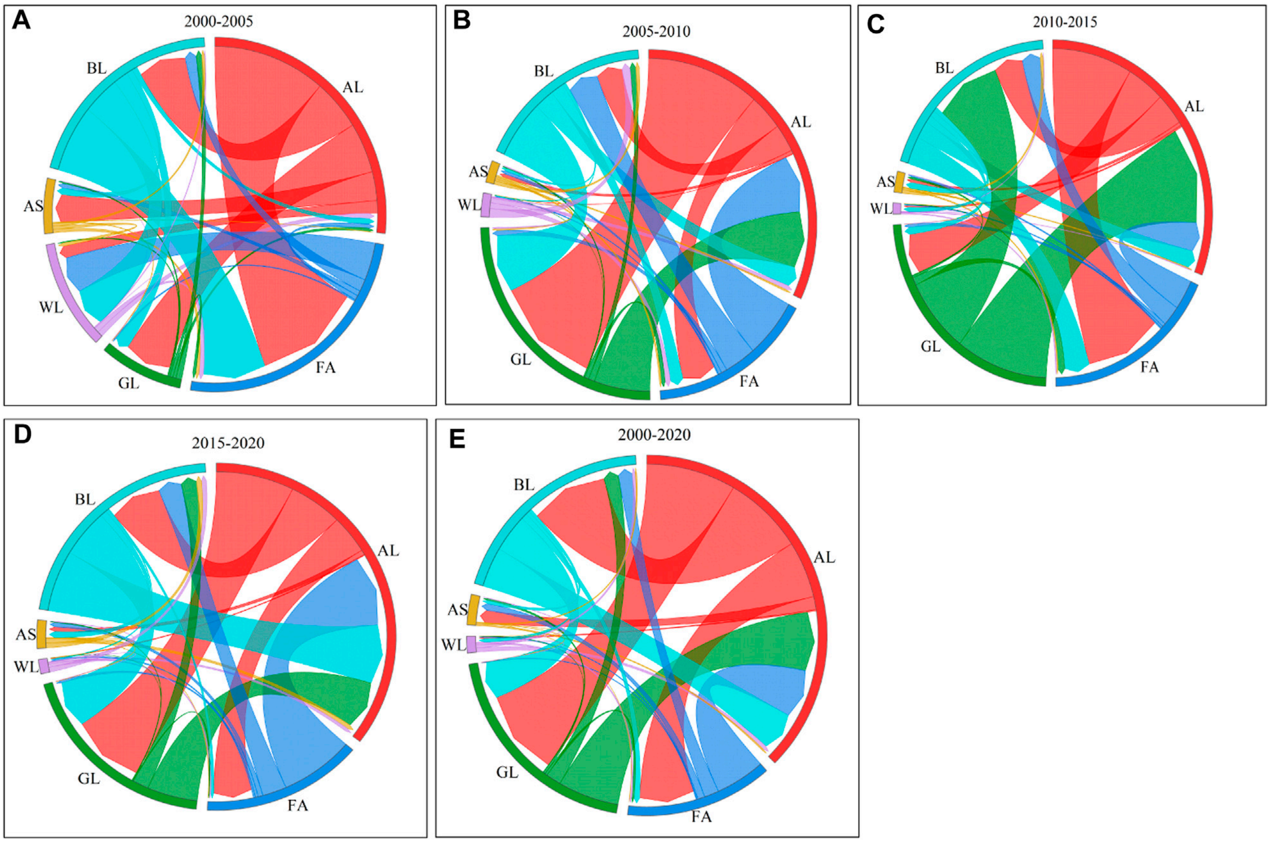

FIGURE 4
(A–D) shows the land use types transition sources and flows in 2000–2005, 2005–2010, 2010–2015, and 2015–2020, respectively, and **(E)** shows the study period of 2000–2020; with (AL) Agricultural land, (WL) Wetland, (AS) Artificial Surfaces, (FA) Forested areas; (GL) Grassland, and (BL) Bare land in Thiès Region.

TABLE 4 Land use matrix in Thiès region (km²) from 2000 to 2020.

Land use types in 2000	Land use types in 2020							
	Agricultural land	Artificial surfaces	Forested areas	Grass land	Bare land	Wet land	Total - 2000	Loss
Agricultural land	2178.49	87.18	380.81	601.80	540.17	8.82	3797.27	1618.7
Artificial surfaces	10.44	59.68	1.14	1.91	9.46	0.24	82.87	23.19
Forested areas	335.48	47.29	282.26	5.26	98.77	6.94	776.00	493.75
Grassland	411.70	14.95	16.73	360.66	102.51	1.25	907.81	547.15
Bare land	266.79	20.58	40.35	253.86	403.56	23.57	1008.71	605.14
Wetland	27.57	2.14	13.71	0.23	21.74	30.46	95.85	65.38
Total - 2020	3230.48	231.82	734.99	1223.71	1176.21	71.29	6669.51	—
Gain	1051.98	172.14	452.73	863.05	772.65	40.82	—	—
Total shift	−566.80	148.95	−41.01	315.90	167.51	−55.02	—	—
Temporal index (%)	−1.667	30.589	−0.396	2.749	1.318	−1.789	—	—
Spatial Index (%)	−8.498	2.233	−0.615	4.736	2.512	−0.368	—	—

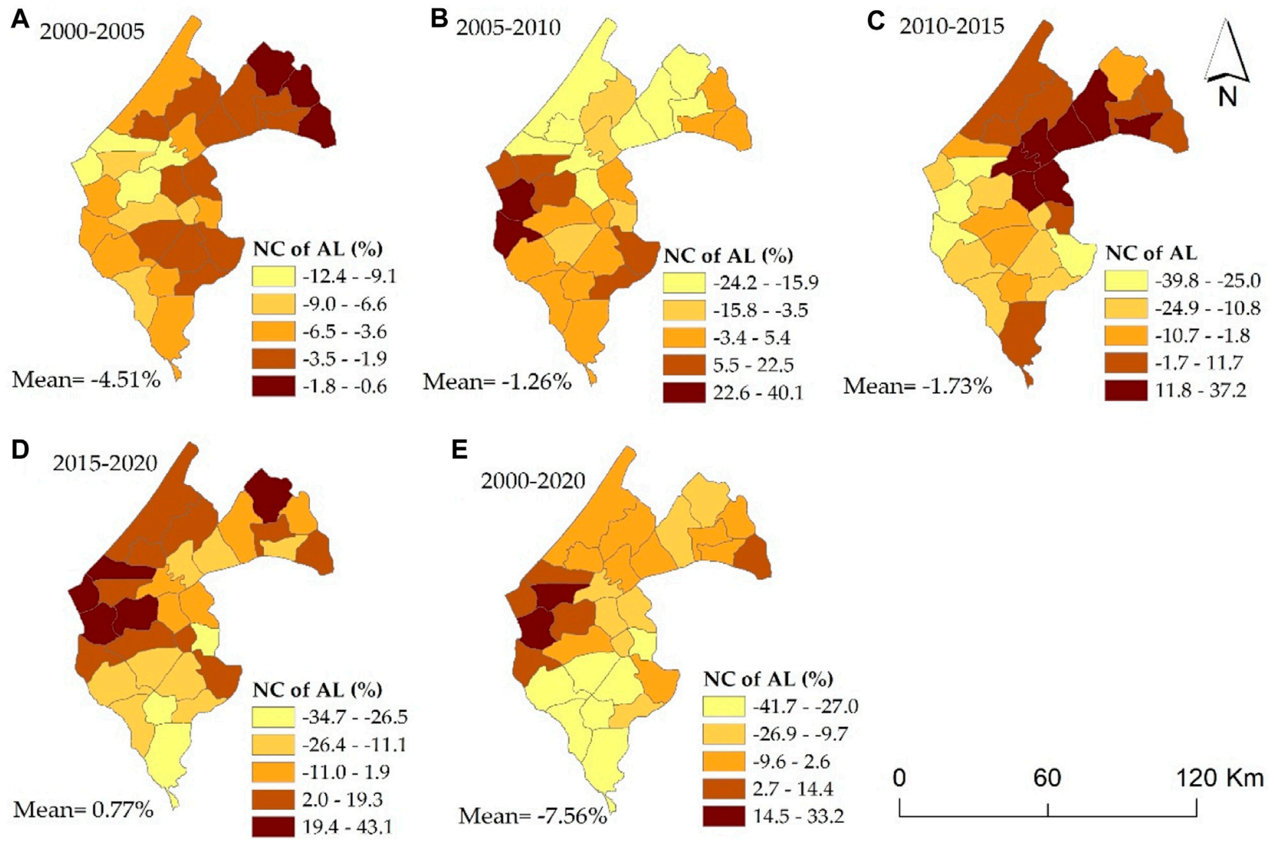

FIGURE 5
(A–D) shows the Spatial distribution of Net Transition of Agricultural Land (NC of AL) in 2000–2005, 2005–2010, 2010–2015, and 2015–2020, respectively, and **(E)** shows the study period of 2000–2020 in Thiès region, Senegal.

transition of agricultural land from 2010 to 2015 was similar to the above description. This period records a coefficient of variation of about −10.23 with an average net transition of −1.73 km^2. These cases were −39.81% in the commune of Mont-Rolland and 37.20% in the commune of Koul. In Koul, bare land contributes approximately 41.03 km^2; in Mont Rolland commune, forested areas dominate 81.06 km^2 for this transition. From 2015 to 2020, the net transition was 43.09% in Noto G. Diama, compared to −34.73% in Sandiara. The coefficient of variation was 25.03 from 2015 to 2020.

During the study period (2000–2020), the coefficient of variation was about −2.22 (Figure 6). The spatial distribution of the net transition of agricultural land was in Mont Rolland commune, at approximately 33.22%. In this amount, forested areas lost about −43.99 km^2, which appears to have been the more common land use type during the agricultural land transition. In the Sandiara commune, the spatial distribution was −41.73%. Bare land was the most critical land use category, contributing to the loss of agricultural land at approximately 55.52 km^2. With an average of −7.56%, the agricultural land transition remained unequally distributed in the Thiès region from 2000 to 2020. In sum, Figure 5B highlights the relatively substantial dispersion. In other words, they are not significantly correlated regarding agricultural land transitions between the communes. The R^2 coefficient was 0.3964 from 2000 to 2020. Consequently, it appears that the potential driving factors may be different.

Analyze the temporal distribution of net transition agricultural land

The temporal distribution of agricultural land net transition was nearly identical for all communes between 2000 and 2005, with an average of −15.53% (Figure 7). The temporal evolution of the net transition of agricultural land was −13.55% in the Ndiass commune and −16.69% in the Darou Khoudouss commune. From 2005 to 2010, Touba Toul commune recorded the highest temporal index of 303.62%. Or, compared with the average period (26.55%), the lowest speed was localized in Marouane commune, approximately −14.17%. From 2010 to 2015, the average temporal index was around 15.95%. Hence, this average has many characteristics because about 140.09% of net conversion is noted in the Koul commune, compared to the lowest of −15.84% in the Mont-Rolland commune. In contrast to the previous period, the speed of 2015–2020 was high, with an average of 17.59%. The highest speed was related to Noto G. Diam (188.17%) and the lowest in Nguiene commune, at −15.22%. In short, the inter-period analysis of the time distribution of the agricultural land net transition showed that the speed varied from commune to commune.

The study period was better analyzed to understand the characteristics of agricultural land's net transition. The average speed from 2000 to 2020 was approximately 0.072%. This average hid several disparities within the commune. Twenty of

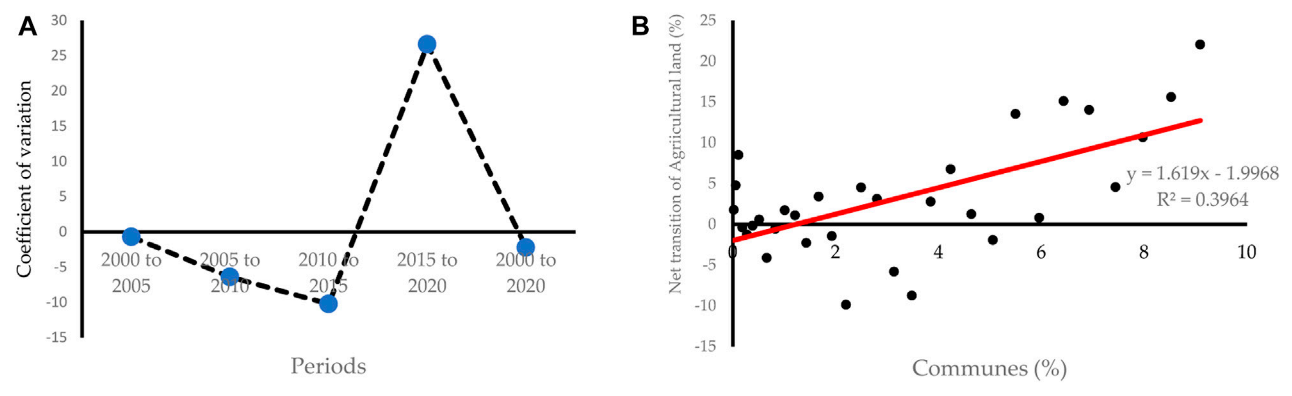

FIGURE 6
Measuring the degree of spatial balance or imbalance of agricultural land net transition **(A)**, variation's coefficient, **(B)** linear regression from 2000 to 2020.

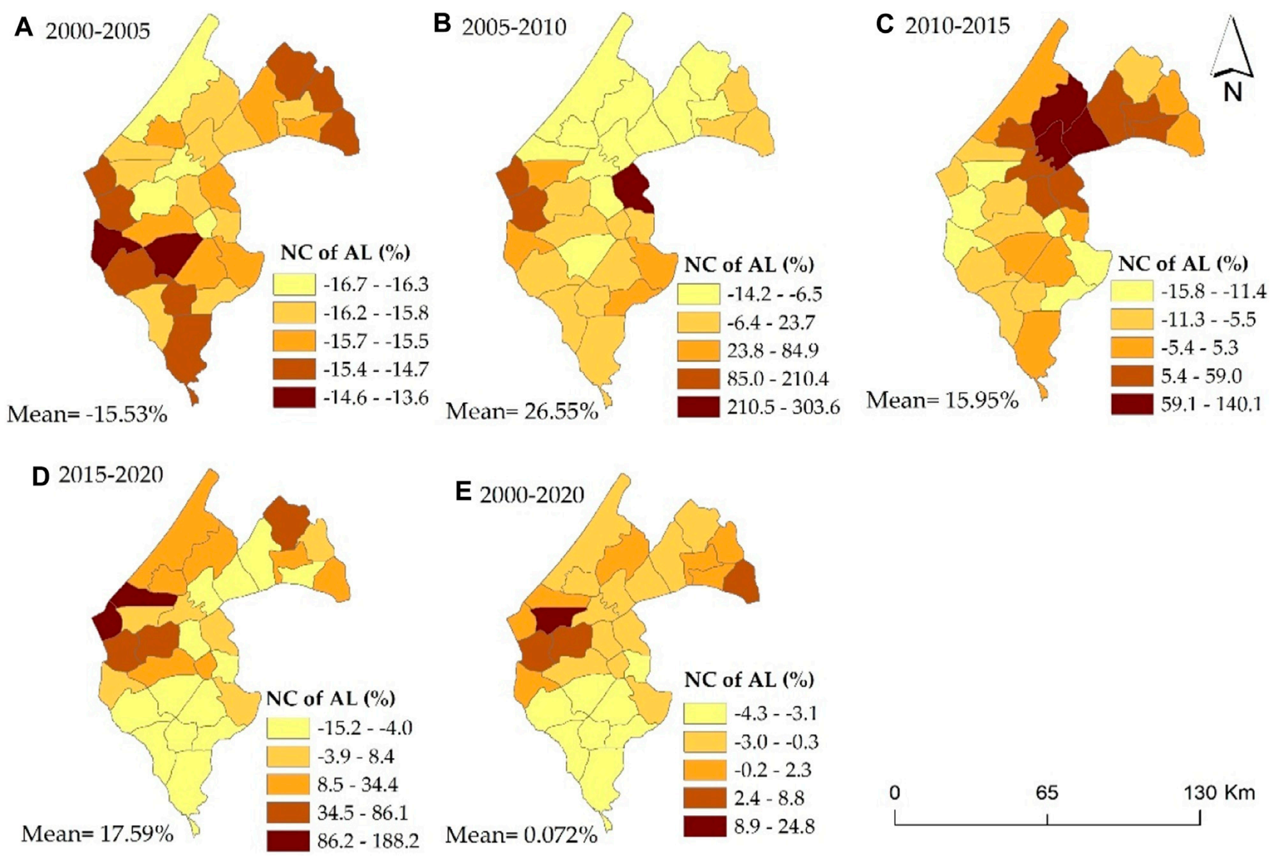

FIGURE 7
(A–D) shows the Temporal distribution of Net Transition of Agricultural Land (NC of AL) in 2000–2005, 2005–2010, 2010–2015, and 2015–2020, respectively, and **(E)** shows the study period of 2000–2020 in Thiès region, Senegal.

the thirty-one communes investigated presented a negative speed. This negative value was located in Koul (−0.35%). Or, at −4.33%, the Sandiara commune had the slowest speed. The Mont Rolland commune (24.84%) recorded the most critical speed among the communes, recording a gain. Or, the commune of Pekess presented less speed by 0.18%. In this amount, Mont-Rolland recorded a net transition of agricultural land of 56.00 km^2 and Sandiara of −60.41 km^2. As a result of this analysis, despite the study being conducted in the same area, the spatial and temporal repartition of the net transition of agricultural land in the Thiès region displayed several characteristics that could be attributed to various economic and social factors.

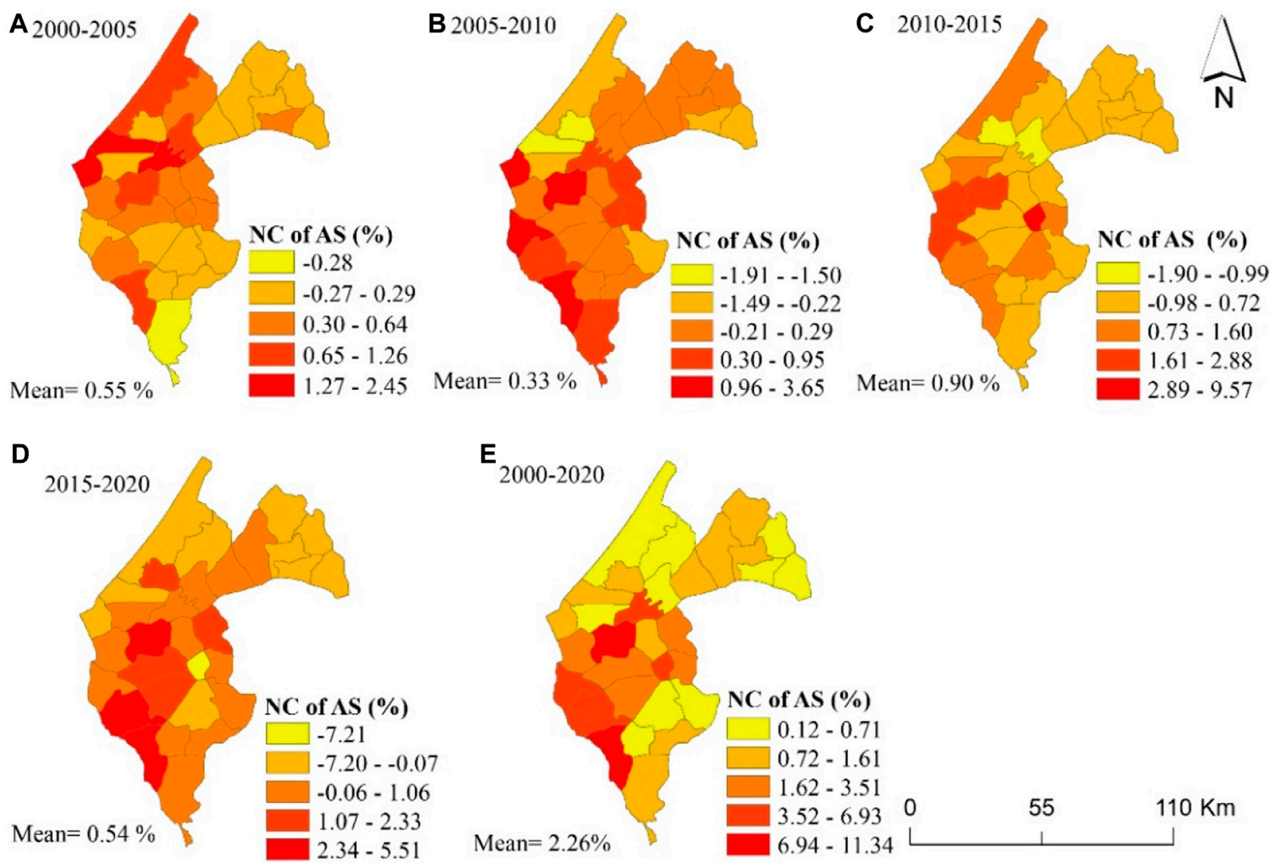

FIGURE 8
(A–D) shows the spatiotemporal intensity index for the transition of Agricultural Land (ALI) measuring according to the Net Conversion of Artificial surfaces (NC of AS) in 2000–2005, 2005–2010, 2010–2015, and 2015–2020, respectively, and **(E)** shows the study period of 2000–2020 in Thiès region, Senegal.

Evaluated the intensification of agricultural land transition

This section examines the intensity transition on agricultural land. In fact, from 2000 to 2005, the rate of artificial surface conversion was 2.50% in the Noto G. Diama commune. The conversion of agricultural land to artificial surfaces covered approximately 4,006 km^2 in this commune. Similarly, Cherif Lo (1.81%) and Diender Guedj (1.91%) achieved high results. The proportion of agricultural land in this net transition of artificial surfaces was 2.63 km^2 and 2.45 km^2, respectively. Alternatively, the net transition of artificial surfaces in Ngueniene commune was −0.28%, and the cause of the decrease in artificial surfaces was wetland by 1.26 km^2. Between 2005 and 2010, the Malicounda commune experienced an essential transition of 3.65%. Fandene commune occupied second place with 2.21%. Malicounda lost approximately 6.45 km^2 of agricultural land to the profile of construction land, while Fandene lost about 1.55 km^2. We noted that eight communes recorded a negative value during this period—for instance, Mont-Rolland commune −0.055%—and bare land contributed to this loss.

As shown in Figure 8, from 2010 to 2015, the average intensity was 0.9%. The highest intensity of artificial surfaces was localized in Ngoudiane commune at 9.57%. This percentage was the highest for all the previous periods. Agricultural land (2.46 km^2) and bare land (3.5 km^2) represented the land use types that contributed to the significant value of construction land. The intensity was lowest in Taiba Ndiaye commune (−19%), whose bare land (3.05 km^2) has caused this phenomenon. Between 2015 and 2020, the results in Malicounda (5.51%) showed diminished intensity compared to the previous period. In this commune, agricultural land losses add about 3.38 km^2 to the profile of construction land. Then, the Sindia commune occupied the second place at approximately 4.52%, and the loss of agricultural land to the artificial surfaces profile was more critical than in the Malicounda commune, with 5.97 km^2. Globally, the inter-period results show that the artificial surface intensity is moderately high. Even though the causes and effects of this change are different, we thought that the amount of agricultural land turned into artificial surfaces was significant.

The study period was a comprehensive pivot to understanding the global intensity of the net transition of construction land. The Malicounda commune records the highest value at 11.34%. In this commune, agricultural land loss to artificial surfaces was about 20.20 km^2. This loss from agricultural land to artificial surfaces was approximately 8.79 km^2 in Fandene and 11.99 km^2 in Sindia commune, with an intensity of 9.82% and 6.93%, respectively. Or, the Thilmakha commune (0.1%) records the lower net transition, and the loss of agricultural land to artificial surfaces was about 0.296 km^2. Globally, 31 communes were registered, with 15 having a percentage higher than

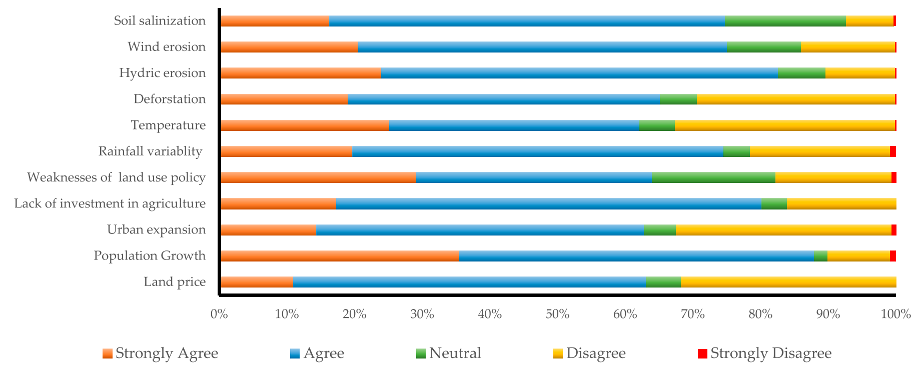

FIGURE 9
Farmer's perception of the potential driving forces of agricultural land transition in Thiès region.

1%. Geographically, these communes were located southwest of and central to our study area (Figure 8E). Consequently, this study's transition from agricultural land to artificial surfaces was significant. Therefore, the influence of bare land on the net transition of construction and agricultural land is not negligible and needs a comprehensive investigation.

Farmer's perception of agricultural land transition

A growing body of literature agrees that socio-economic development occurred during the agricultural land transition (Kanianska, 2016). Conversely, according to farmers' perceptions, natural environmental factors drive the agricultural land transition. Firstly, as shown in Figure 9, if we focus on the "strongly agree" response, the socio-economic factors, namely, the population growth factors (35.38%), record the most important "strongly agree" response among the other driving factors. Weaknesses follow it in the land use policy factor (29.06%), considered a political driving factor. Regarding natural and climatic factors such as temperature and hydric erosion, they recorded 25.13% and 23.93%, respectively. Secondly, Table 5 showed that the relationship between soil salinization and deforestation was the most significant, with 0.971. In the same sense, wind erosion and soil salinization (0.944) occupied the second place. In that setting, the main driving factors that may facilitate the agricultural land transition in Thiès' region are the natural environment and biophysical factors. Alternatively, among socio-economic factors, one of the most interesting results was observed between the lack of agricultural investment and land policy (0.695). This context was followed by land policy and land prices (0.586). The lower value (0.246) was observed between urban expansion and population growth. Consequently, it seems that the manifestation of agricultural land transition is not the same between industrial and developing

TABLE 5 Assessment of the farmer's perception of the potential driving factors of agricultural land transition in the Thiès region.

	1	2	3	4	5	6	7	8	9	10
Land price	x									
Population growth	0.362	x								
Urban expansion	0.378	0.246	x							
Lack of investment in Agri	0.819	0.614	0.446	x						
Land policy	0.586	0.570	0.380	0.695	x					
Rainfall variability	0.813	0.507	0.540	0.893	0.714	x				
Temperature	0.801	0.633	0.648	0.793	0.861	0.835	x			
Deforestation	0.838	0.600	0.699	0.821	0.671	0.897	**0.938**[(4)]	x		
Hydric erosion	0.463	0.502	0.636	0.502	0.492	0.587	0.659	0.697	x	
Wind erosion	0.691	0.661	0.794	0.822	0.739	0.875	0.925	**0.943**[(3)]	0.760	x
Soil Salinization	0.735	0.555	0.813	0.715	0.611	0.837	0.906	**0.971**[(1)]	0.690	**0.944**[(2)]

Note: Bold represented the coefficients are significant.
p-value [1)] = $p > 6.8E-07$.
p-value [2)] = $p > 1.2E-05$.
p-value [3)] = $p > 1.40E-05$.
p-value [4)] = $p > 2.0E-05$.

countries. In conclusion, farmers' perceptions of socio-economic drivers of agricultural land transition in this region are insignificant compared to natural environmental drivers.

Discussion

Economic driving mechanism

According to the findings of this study, between 2000 and 2020, a diverse range of factors, including those related to the economy, politics, and nature, may significantly impact Thies region's agricultural land morphology. An in-depth exploration of the dynamics and existing problems in farmland morphology is crucial to formulating targeted protection policies (Lyu et al., 2021). Therefore, understanding agricultural land use dynamics in transition is critical for ensuring national food security in developing countries like Senegal. The agricultural land resource is an indispensable production factor for national economic development and farmer households. Economic growth generally leads to increased demand for land and changes in land utilization patterns (Chen et al., 2020). This situation is a reality in Thiès because the results show that between 2000 and 2020, the net transition of artificial surfaces was about 148.95 km^2 and evolution of 210.7%. According to ANSD, between 1976 and 2019, the regional urbanization rate increased steadily from 29% to 51.7%, respectively. Then, Thiès region has served as a secondary region of Senegal to promote socio-economic development (Faye and Du, 2021). Promoting socio-economic development requires constructing new infrastructure, and the lack of comprehensive land policies may induce agricultural land transition. This context is essential because fast urbanization appears to be a factor that may induce the transition of agricultural land. Expansions of housing, transportation, industry, retail sales, schools, and other developments are driving farming off of land (Francis et al., 2012). The analysis demonstrates that the communes of Fandene (Department of Thies) and Malicounda (Department of Mbour) have the most intense agricultural land transition. Or, in the North, the agricultural land use seems to have been caused by other factors such as climatic according to the survey. Then, the rural exodus and other economic activities, such as tourism in the western part of the Thies region, partly explain this rapid increase in the urban population. The majority of the population and economic activity of the Thiès region is concentrated in these communes, which serve as the city centers. The migration percentage for employment problems represents 13.3% in the Thies region for ages 15–35. Accordingly, the migration led almost to urban spatial issues and agricultural land abandonment. So, as cities grow and spatially expand in the Thiès region, agricultural land is converted into residential land (Picard and Selod, 2020).

In addition, the Thiès region was one of the backbone regions of Senegal's mining industry. Previous studies highlight that mining activity in the northern part of the region, such as Taiba Ndiaye commune, strongly impacts the population's socio-economic life (Henri Marcel SECK, 2021), including agricultural land use. So, this situation can justify the rapid conversion of agricultural land use to bare land in this part of our study area. Regarding infrastructure, this area has been chosen to host significant structuring projects such as Blaise Diagne International Airport and the Special Integrated Economic Zone. In addition, there are the urban poles of Diamniadio and Lac Rose, the industrial zone of Diamniadio, and the motorway projects. In this situation, the demand for land became more and more significant. The survey results did not highlight this spatial pressure on land, which revealed the lowest relationship between urbanization and population growth at 0.246. Thus, there is uncertainty regarding the influence of urban expansion on agricultural land transition. As a result, the social survey results demonstrate that urbanization was most significant in the western part of our study area, like the Sindia commune. This region's part of the west appears to have the highest urbanization because of its proximity to Dakar (the capital of Senegal). In 2017, the Dakar region accounted for 39.5% of Senegal's economic units, whereas Thiès and Diourbel accounted for 11.5% and 9.9%, respectively (Ministry of Economy Finance and Planning, 2017). In short, based on the spatial and survey data, we thought that the link between rapid urbanization and population growth might cause the rapid change from farmland to no agricultural land in our study area.

Land policies and cultural driving mechanism

This section's policies and cultural driving factors are the dualities between state land use policies and traditional land use practices. Since the Industrial Revolution, the economic development of Western Europe and North America has been characterized by continuous urbanization accompanied by a gradual phasing-in of urban land property rights over time (Cai Yongyang, 2015). Conversely, in developing countries such as Senegal, urbanization has been accompanied by several conflicts. The issue is the competition between land users, weak land tenure, etc. For instance, the drastic loss of livelihoods, including agricultural land, in the peri-urban areas of Sebougou (Mali) is primarily related to the crisis in Mali's land management system (Coulibaly and Li, 2020). So, the agricultural land transition process may be more complex in Senegal than in industrial countries. The weak land use plan may significantly affect the rapid agricultural land transition. For instance, the duality between customary and modern land policy led to many issues in Thies. A relevant study highlights that on the West African continent, the land is mainly accessed through an informal and customary channel (Durand Lasserve and Selod, 2013). So, converting agricultural land use to another no agricultural land activity became more significate. This assertion shows that land on Thies region remains subject to traditional practices.

Land tenure is closely related to culture and institutional values in society (Suryadi et al., 2021). In Senegal, Law N*64–46 of 17 June 1964, governs land use management in Senegal and stipulates that land belongs not to the state, territorial communities, or users but to the "Nation" (Niang, 2017). In other words, this law stipulates that most of the land in Senegal is national domain land that does not belong to the people who use it because the law has abolished customary rights. According to the National Agency for Demography and Statistics, approximately 88.61% of plots were not registered between 2017 and 2020. This situation shows that agricultural land remains under traditional dominance, and the mode of land acquisition is passed down from generation to generation. As a result, landholders can sell, transfer, or reuse it for other purposes without significant legal constraints. Hence, no registered land became an obstacle not only to agricultural development but also caused rapid urbanization (Faye, Du and Zhang, 2022). Accordingly, the continuous fragmentation of agricultural land from generation to generation without an adequate policy for its protection remains a reality. So, the dominant morphology changes in Senegal, particularly in the Thiès region, is heavily influenced by property rights and a lack of agricultural investment. In another work, the lack of land policies is often seen as the main factor in agrarian land transitions. Political and economic reforms are imperative for farming and related sectors. But today, it is difficult for developing countries like Senegal to initiate specific reforms. This situation arose because the politic of decentralization, for example, remains closely linked to the obligations of structural adjustment policies and is constrained by the logic of liberal reform (Boutinot, 2003). Then, according to FAOSTAT data, over the period 2000–2020, the average credit to agriculture was about US $48.82 million. This situation seems to indicate that external financial institutions partly finance Senegalese agriculture. As a result, the agricultural policy reforms, including Senegal's land system, remain challenging and complex. In summary, this may imply that when the social development level is low due to the unclear property rights of cultivated land and underdeveloped agricultural technology, the social awareness of cultivated land protection is relatively weak, and cities are disorderly expanded (Lv et al., 2022).

Natural environment driving forces

This study's main factors are natural factors such as rain variability, deforestation, and temperature. Rain variability has a significant impact on the evolution of sown land use. In fact, in Africa, particularly in the Sahel, after the rainy periods of the 1960s, many researchers noted rain anomalies in the early 1970s (Ambiente, 2016). This situation was pointed out, too, in Senegal. Tappan et al. (2004) revealed that rainfall in the Groundnut Basin ranged from 400 to 800 mm in the 1960s to 200–600 mm in the 1990s (Tappan et al., 2004). Then, according to the data collected by the National Agency for Civil Aviation and Meteorology (ANACIM), the average rainfall from 2000 to 2020 was 461.65 mm. Or, this average hid several disparities. For instance, in 2000, the average was 607.90 mm, compared with 317.90 mm in 2005. These analyses show a difference of 290 mm. The above discussion shows that rain remains a problem in our study area because Senegal's agricultural production still depends entirely on the rainy season. This variability's consequences are reflected directly in farm productivity and yield (FAYE Bonoua, 2016). In addition, low annual rainfall, frequent dry spells, and the shortening of the rainy season affect the vegetative cycle of crops (Faye Mbagnick, 2018). During the social survey, several farmers attested that their agricultural land was decreased, and the most critical factor was rainfall, weak agricultural investment, and so on. Therefore, weak agricultural productivity diminishes agricultural land area, directly inducing agricultural land abandonment and population migration. This is because agriculture is Senegal's main activity (ANSD, 2020). The household, affected by the weak agricultural productivity, moves to a big city such as Dakar to look for new activities. This statement may explain the strong relationship between rainfall and lack of investment in agricultural land (0.893). However, agricultural production depends on rainfall (Isabelle et al., 2019) and the availability of outputs. In the same sense, the temperature data from the same period from 2000 to 2020 reveal that in 2000 the average temperature was 24.85°, and in 2020 it was 28.01°. So, the temperature was gradually rising. This augmentation of the temperature seems to have a negative impact on agricultural land use, as shown by the survey results (0.971).

Desertification is land degradation in drylands resulting from various factors, including climatic variations and human activities (European Union, 2011). In other words, land use and cover changes, such as deforestation, affect the climate system and land-atmosphere interactions (Sy et al., 2017). In that context, agricultural land transition and deforestation will be inextricably linked. This assertion was supported by our research, which discovered that the net change of agricultural land and the net transition of forested areas decreased during the study period. The social survey results indirectly show a high relationship between deforestation and wind erosion (0.943). This relationship induces subsequent socio-economic consequences, such as agricultural productivity. Relevant studies show that rural economic development (Liu et al., 2014) and urbanization (Rondhi et al., 2018) are the primary forces driving the transition from farmland to non-agricultural land use. As revealed by the social survey, the relationship between rainfall variability and deforestation was strong (0.897) from then on. Furthermore, according to survey results, many smallholders believe the garden could be an excellent solution for dumping this matter in the event of less rain. In contrast, the lack of financial means is critical for obtaining the solution. In addition, to support their families, many sell agricultural land or choose migration to diversify their income. So, this practice was seen as facilitating agricultural land transition and fragmentation.

Bio-physical driving forces

Natural factors like rain runoff and bio-physical drivers like hydric erosion are closely linked. Hence, the consequences of the decrease in rainfall are reflected in Senegal by the degradation of the natural environment. Then, drought leads to the degradation of the vegetation cover, the soils being subjected to erosion and runoff, and the accentuation of acidification and salinization (Ndong, 1995). Hence, Senegal's forests have decreased from 4.4% in 1965 to 2.6% in 2000 (Tappan et al., 2004). Similarly, our results show that forested areas have dropped by −41.01 km^2. In that setting, the forested areas in Senegal continue to be reduced. Consequently, forest degradation may affect agricultural land quality because previous studies have highlighted that soil organic carbon is crucial in regulating soil quality functions and ecosystem services (Amoakwah et al., 2022).

Multiple physical, chemical, and biological degradations increasingly threaten the soil. Soil erosion affects 56% of the land surface worldwide (Van Oost et al., 2007). Specifically, soils in Africa affected by moderate to severe water erosion cover more than 12 million hectares, or 18.5% of the total national territory (Faroukh Tsouli A, 2017). Then, the Groundnut Basin of Senegal (including our study area) is confronted with chemical and physical-biological degradation, which has become more intense. Thus, the

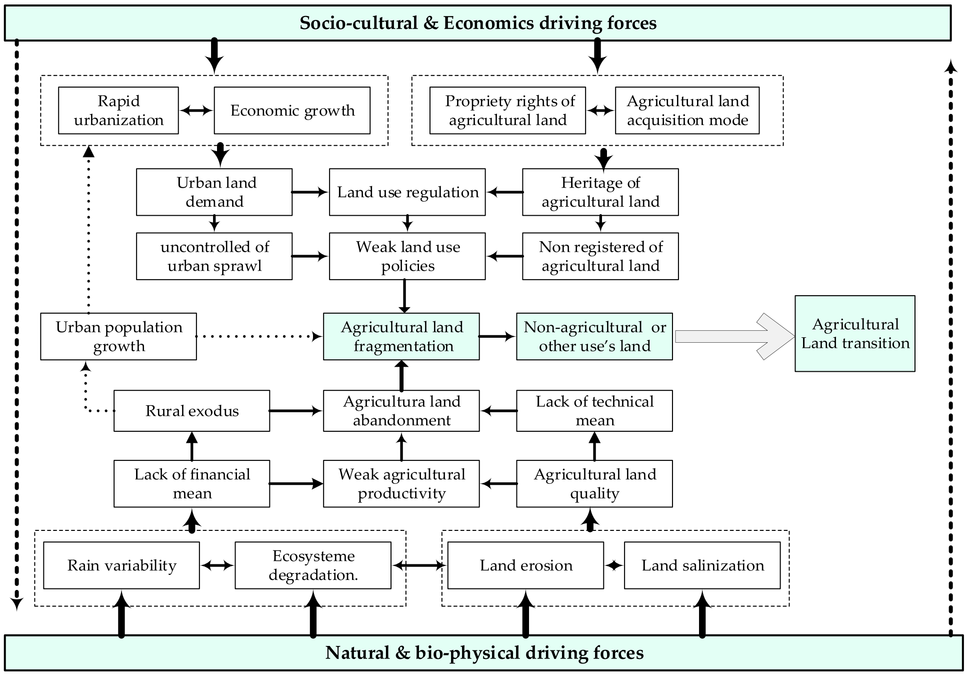

FIGURE 10
The flowchart summarizing the discussion section of the study.

soils are impoverished, restructured, and chemically exhausted by wind, water erosion, and recurrent droughts (Reseau Agro-Innov, 2017). The survey results show that the relationship between soil salinization and hydric erosion was about 0.690. This situation signifies that biophysical driving forces like wind and water erosion are some of the main factors that may facilitate the agricultural land transition in the Thiès region.

Consequently, agricultural land degradation was occurring in Senegal's Thiès region. This continuous degradation may impact agricultural productivity because agricultural soil erosion is thought to perturb the global carbon cycle (Van Oost et al., 2007). Hence, the deterioration of forested areas significantly impacts agricultural land quality. According to the above background, the agricultural land transition is an incentive-driven process (Rondhi et al., 2018). According to the social survey data and the summary in Figure 10, biophysical factors appear to be one of Thies region's most important driving factors that induced agricultural land transition. However, the study clarifies that social, economic, and natural factors are all tied together in the agricultural land change in our study area.

This discussion has shown that the Thiès region's agricultural land faces several driving factors, particularly natural factors, which have been identified as the main factors. From then on, the first recommendation regarding agricultural land protection is implementing a comprehensive land use reform policy. This context exists because implementing clear rules between users is the first key to protecting it. So, according to the complexity of the land management system in Senegal, reforming land tenure must cooperate with its complexity rather than attempt to substitute customary land practices. From an economic point of view, we think that increasing agricultural production, creating new jobs, and raising income may stop agricultural land from changing because, according to survey results and interviews, agricultural land changes rapidly when abandoned or sold.

Conclusion

Agriculture land dominates the Thiès region's land use morphology, accounting for 48% of the total land area. The main objective of this article was to understand the characteristics of the transition of agricultural land in the Thiès region from a quantitative point of view and a spatial and temporal evolutionary point of view. From a quantitative point of view, agricultural land decreased from 2000 to 2020 by −588.66 km^2. Grassland was the most critical land use type to have participated in this loss. Also, the share of Artificial surfaces was about 148.95 km^2 during the same period. From 2000 to 2020, the commune of Mont-Rolland was dominated by spatial characteristics (33.22%). Alternatively, agricultural land use loss in the Sandiara commune is 41.73%. For the temporal distribution, the average speed from 2000 to 2020 was approximately 0.07%. The net transition was negative in Koul, with an amplitude of −0.35%. Or, the commune of Pekess increased its speed by 0.18%. In the end, this analysis shows that even though the study occurred in the same area, the spatial and temporal distribution of the net transfer of agricultural land in the Thiès region had different features. The intensity of agricultural land measured varied from one area to the next due to the net transition of construction land. The intensity was high in Malicounda commune, where the net transition of artificial surfaces was 11.34%. In this commune, agricultural land loss to artificial surfaces was about 20.20 km^2. This loss from agricultural land to Artificial surfaces was approximately 8.79 km^2 in Fandene and 11.99 km^2 in Sindia commune, with an intensity of 9.82% and 6.93%, respectively. With the R^2 about

0.396, they are not significantly correlated regarding agricultural land transitions between the communes. Additionally, the social survey data show a substantial relationship between natural factors and socio-economic drives. The most significant was the nexus between soil salinization and deforestation. In contrast, the relationship was about 0.246 for population growth and urbanization.

This research contributes to using an integrated analysis method to understand the causes of agricultural land transition while highlighting policy flaws that may lead to a rapid agricultural land transition. So, from this contribution, the study also enhances the theoretical approach and methodology for assessing the mean potential driving factors in developing countries such as Senegal. From these results, the policy implications highlighted in this study rank from lessons to strengthen agricultural land use reforms to promoting the awareness of land use policy, particularly agricultural land. Encouraging land consolidation is also urgent to optimize agricultural production and avoid land fragmentation. Consequently, the study highlighted certain limitations that should be addressed in future research. Firstly, the contribution of bare land to agricultural land transition was high. So, future research may focus on the details of the influence of bare land on agricultural land. The natural driving factors were much more visible than the socio-economic driving factors. Alternatively, the population continues to grow rapidly in tandem with socio-economic development. As a result, an in-depth investigation may be required to determine the impact of socio-economic factors on agricultural land transition in the Thiès region.

Data availability statement

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

Author contributions

Conceptualization, BF and GD; methodology, BF; software, BF; validation, BF, GD, QL, TS, EM, and RZ; formal Analysis, BF; investigation, BF; resources, BF; data curation, BF; writing—original draft preparation, BF; writing—review and editing, BF, GD, QL, TS, EM, and RZ; visualization, BF, and GD; supervision, GD; project administration, DG. All authors contributed to the article and approved the submitted version.

Funding

This research was funded by the National Key R&D Program of China, grant No. 2021YFD1500101.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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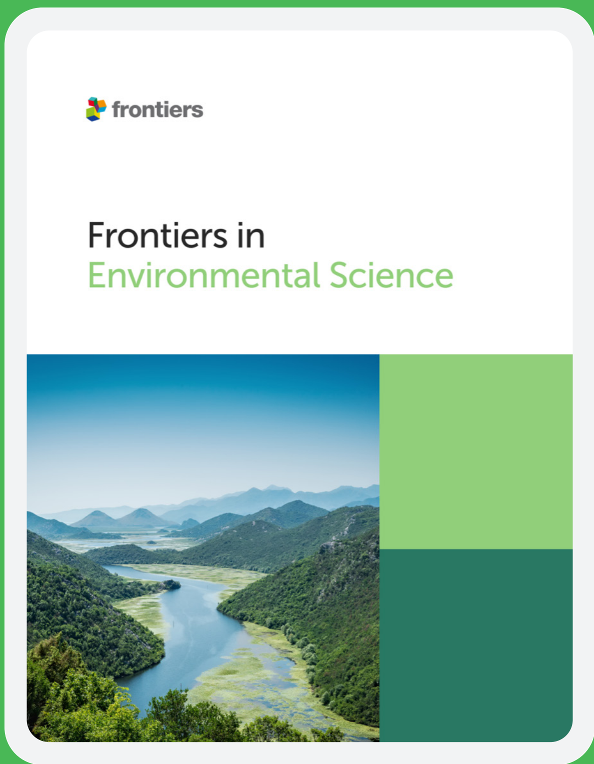

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