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Original Research

Coupling Coordination Analysis of Cultivated Land Quality Evolution and High-Standard Farmland Construction in Arid Oasis Agricultural Areas: A Case Study of Wensu County, China

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Abstract

Understanding the synergistic mechanisms between cultivated land quality and high-standard farmland construction is crucial for sustainable agriculture in arid oasis regions. This study examined Wensu County, China, integrating multi-source data through the PLUS model, fuzzy comprehensive evaluation, and coupling coordination analysis. Results demonstrate that cultivated land quality in 2023 exhibited a mosaic pattern dominated by Grade III land (38.15%), with high-grade land (Grades I-II) concentrated in southwestern alluvial-proluvial fans and low-grade land (Grades IV-V) distributed across southeastern gravelly plains. Projections to 2031 indicate significant quality improvements, with Grade II land area expanding to 385.83 km^2 (36.4% increase), while low-grade land decreases to 274.38 km^2 (4.88% reduction). High-standard farmland construction suitability displays southwest-to-southeast gradients, with 68.5% of cultivated land classified as highly suitable (Levels I-III), primarily constrained by hydrological conditions and salinization intensity (factor weight: 16.8%). Coupling coordination degrees exceed 0.5 across 85% of the study area, establishing a west-high, east-low collaborative pattern. Salinization management and irrigation optimization could enhance coordination by 15%-20%. This research develops an integrated “evolution-suitability-coupling” framework, providing quantitative tools for precision farmland management in arid regions and scientific guidance for similar areas along the Belt and Road Initiative.

Keywords: arid oasis, cultivated land quality, high-standard farmland, PLUS model, coupling coordination degree

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Introduction

Cultivated land represents a fundamental resource for maintaining food security and ecological stability [1], yet faces intensified challenges within arid oasis agricultural systems [2]. Arid regions encompass approximately 41% of the global terrestrial surface area while supporting over 38% of the world's population. Oases constitute critical components of arid landscapes, serving as primary hubs for human activities, socioeconomic development, and ecological processes [3]. However, water scarcity, soil salinization, and land degradation substantially limit cultivated land quality enhancement [4]. China's arid oasis agriculture exhibits characteristic patterns of irrigation dependence, ecological vulnerability, and spatial fragmentation [5-7]. Wensu County, representing a typical oasis agricultural region along the northern margin of the Tarim Basin, demonstrates cultivated land quality dynamics directly linked to sustainable development of the grain and oil production bases across the southern Tianshan Mountains [8, 9].

A comprehensive understanding of cultivated land quality constitutes a primary objective for achieving sustainable food security [10]. Given the multifaceted nature of cultivated land quality, assessment cannot rely on a single soil quality indicator or on direct laboratory measurements. Contemporary research has evolved from univariate soil fertility evaluation toward multidimensional comprehensive analysis, employing measurable soil properties as quality assessment indicators [11]. Consequently, indicator system development requires comprehensive datasets encompassing physical and chemical properties that reflect soil fertility status, ecological health, and overall soil condition [12]. Nevertheless, systematic research addressing unique oasis ecological mechanisms remains significantly limited [13-15]. Early cultivated land quality evaluation, exemplified by USDA land capability classification, emphasized qualitative analysis of topographic and soil productivity factors. Subsequently, the FAO Agro-Ecological Zone (AEZ) methodology pioneered the integration of climatic variables into quantitative evaluation frameworks [1, 16].

Policy evolution in cultivated land protection reflects the Chinese government's deepening commitment to land resource management, positioning cultivated land quality and ecological construction as strategic priorities [17]. Contemporary cultivated land protection and quality enhancement initiatives confront evolving challenges and requirements. Research and implementation of cultivated land quality evaluation increasingly serve as foundational elements for protection strategies, including land use planning [18], land consolidation planning [19], permanent basic farmland designation [20], and high-standard farmland construction [21, 22]. These initiatives require scientifically robust cultivated land quality evaluation standards for effectiveness assessment. Therefore, advancing cultivated land quality understanding and evaluation methodologies remains essential for informing protection strategies. Regarding high-standard farmland development, China launched nationwide comprehensive high-standard basic farmland construction in 2011 to enhance cultivated land quality [23, 24]. As a specialized form of cultivated land consolidation, high-standard basic farmland construction (HSBFC) proves crucial for rural development and territorial spatial optimization, supported by land consolidation projects (LCPs) [25]. Construction objectives encompass concentrated, well-equipped, high-yielding, stable, ecologically sound basic farmland with enhanced disaster resistance, suitable for modern agricultural production and management. However, high-standard farmland construction in arid regions encounters constraints from water scarcity and ecological vulnerability, including insufficient irrigation efficiency, limited soil improvement technology adaptability, and incomplete ecological protection systems, hindering the achievement of high-yielding, stable, and ecologically sound objectives.

Since the reform and opening up in 1978, urbanization has driven profound changes in China's cultivated land in terms of the utilization entities and social functions, showing an overall trend of continuous loss [26-28]. This phenomenon has attracted widespread academic attention, with numerous studies focusing on the spatiotemporal evolution characteristics and driving mechanisms of cultivated land at different spatial scales. For example, Lyu et al. [29] analyzed the spatiotemporal patterns of cultivated land system resilience across 30 provinces nationwide, while Liu et al. [30] explored the evolution mechanism of cultivated land fragmentation in Jiangsu Province. However, existing research [31-33] is mostly limited to historical spatiotemporal evolution analysis and lacks the prediction of future patterns under the action of the long-term driving factors, such as policies and human activities. Cellular automata (CA) models are widely used in land use dynamic simulation [34]. Among them, models based on the pattern analysis strategy (PAS), such as FLUS [35], CLUE-S [36], and CA-Markov [37], are superior to traditional transition analysis strategy (TAS) models but still struggle to reveal the mechanisms of the driving factors [38]. In contrast, the Patch-generating Land Use Simulation (PLUS) model proposed by Liang et al. mines conversion rules through the land expansion analysis strategy (LEAS) and combines multiple types of random patch seeds (CARS) modules, integrating the advantages of both TAS and PAS while improving actual landscape pattern simulation capabilities with higher accuracy [39]. Currently, this model has been preliminarily applied to ecosystem service evaluation and land use structure dynamic analysis [40].

In recent years, China's high-standard farmland construction has shifted from "quantity balance" to "quantity-quality-ecology" trinity protection [41]. However, existing studies often treat cultivated land quality as a static variable, overlooking the dynamic evolution mechanisms within the fragile "Mountain-Oasis-Desert" ecosystem [42, 43]. This limitation obscures a critical scientific question [1, 10]: how does the spatiotemporal evolution of cultivated land quality under arid constraints align with the static planning of high-standard farmland construction? To address this gap, this study establishes an integrated evaluation framework (Fig. 1) using Wensu County as a representative case.

The specific research objectives are: (1) to simulate the spatiotemporal evolution of cultivated land quality from 2023 to 2031 using the PLUS model; (2) to evaluate the suitability for high-standard farmland construction by incorporating ecological stability and water-soil constraints; and (3) to diagnose the coupling coordination relationship between quality evolution and construction suitability, thereby providing scientific guidance for precision land management in arid oases.

Materials and Methods

Study Area

Wensu County, China (40°52′-42°21′N, 79°28′-81°28′E) is selected as the study area as it typifies the classic "Mountain-Oasis-Desert" (MOD) ecosystem structure of the Tarim Basin (Fig. 2) [44]. Situated beneath the southern foothills of Tomur Peak in the central Tianshan Mountains, the region features a distinct vertical landscape gradient where northern glaciers supply critical meltwater to the Kumalak and Tailan river systems, establishing a strict irrigation-dependent agricultural model. The region represents a critical transition zone with significant spatial heterogeneity in soil conditions. A 50 km escarpment demarcates the western Kumalak-Toshkan alluvial plain (characterized by fine-textured soil, soil depth > 2 m) from the eastern Tailan-Kalayuleguen proluvial plain (dominated by coarse-textured materials, 15-25% gravel content). This west–east geological contrast provides an ideal setting to examine the spatial differentiation of cultivated land quality. The climatic conditions are hyper-arid (Aridity Index 8.2), with a mean annual temperature of 10.10°C, and precipitation of only 65.4 mm [45]. Although geographically advantageous due to its proximity to the Aksu metropolitan center, the region faces severe ecological stressors, including recurrent spring dust storms (≥ 22 days annually with ≥ grade 8 winds). These combined factors of water scarcity, soil variability, and ecological vulnerability make Wensu a representative laboratory for studying the coupling constraints of high-standard farmland construction in arid oases.

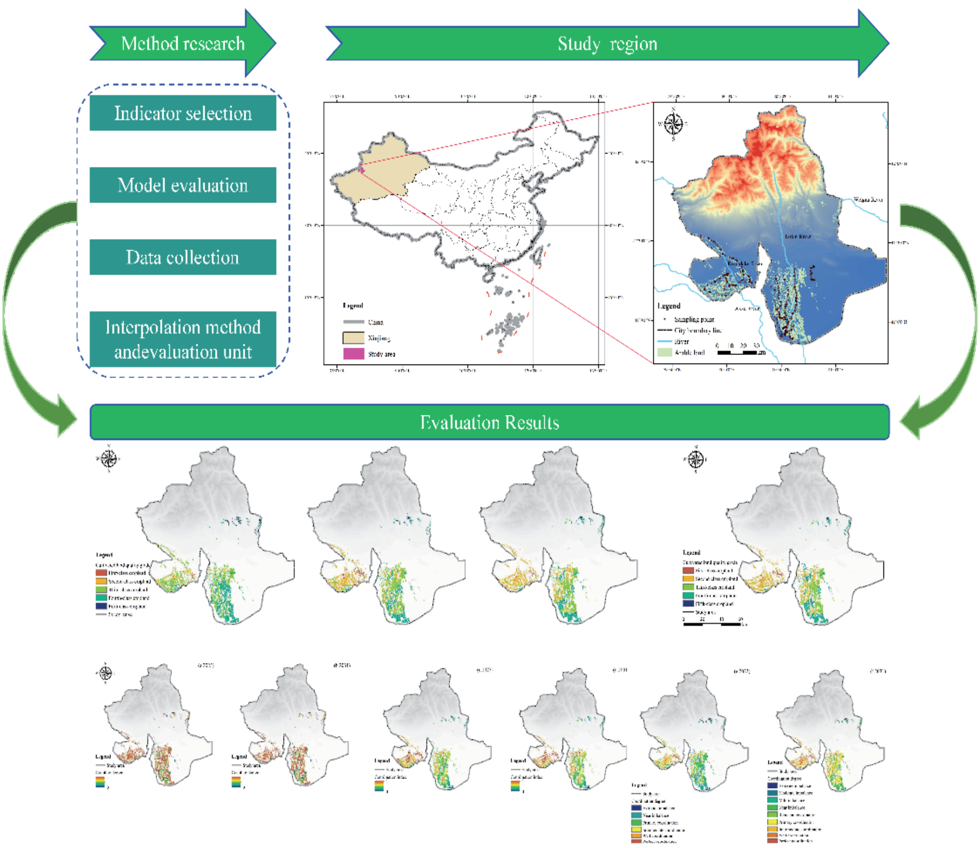

Fig. 1. Research framework.

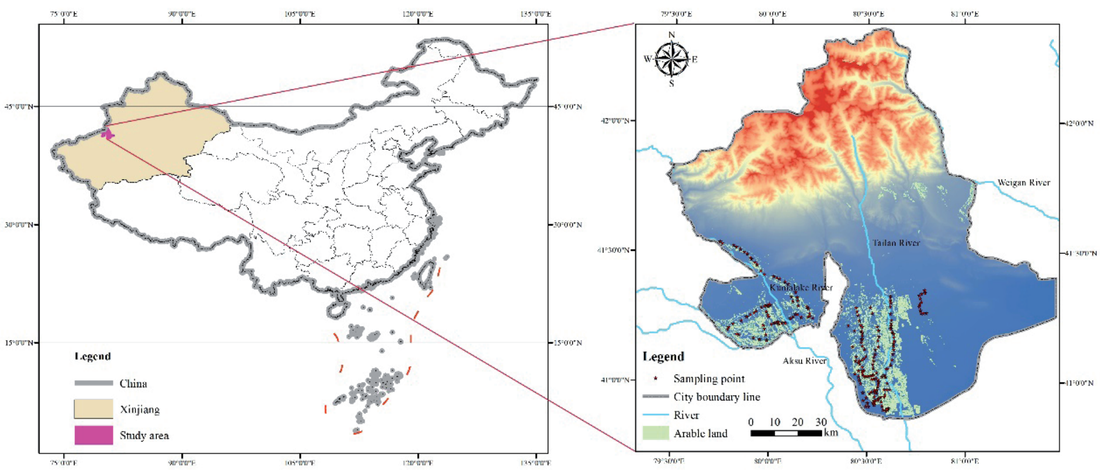

Fig. 2. Geographic location of Wensu County.

Data Sources and Preprocessing

Multi-source Data Integration

The dataset was integrated from field surveys, remote sensing imagery, and official statistical records. In 2023, a stratified sampling campaign collected 200 soil samples across Wensu County (Fig. 2) to analyze the pH, water-soluble salt, organic matter, and texture, strictly following the Soil and Agricultural Chemistry Analysis standards. This was supplemented by historical data from the 2015 sampling points to ensure temporal continuity.

The topographic data (DEM, 30 m resolution) and the administrative division vector data were obtained from the Resource and Environment Data Center, Chinese Academy of Sciences (http://www.resdc.cn/). Crucially, the 2023 farmland boundary vector data were officially provided by the Wensu County Natural Resources Bureau to ensure the high spatial accuracy required for plot-level evaluation.

Evaluation units were generated by overlaying soil maps, farmland boundaries, and administrative divisions in ArcGIS 10.8, resulting in 17,500 basic units. Continuous surface layers for soil nutrients were generated using Kriging interpolation, processed separately for the southern plains and the northern mountainous areas to minimize spatial heterogeneity errors.

Indicator System and Weight Determination

The two hierarchical evaluation systems were constructed based on the national standards and the local arid-oasis characteristics:

Table 1. Indicator weights for cultivated land quality grade evaluation in Wensu County.

Target Layer	Criterion Layer	Indicator Layer	Combined Weight
Cultivated Land Quality Grade Evaluation	Site Conditions	Topographic position	0.075
		Topsoil texture	0.072
		Slope	0.063
	Physical and chemical properties	Soil profile	0.066
		Effective soil depth	0.065
		Salinization degree	0.101
	Soil nutrients	Organic matter content	0.103
		Available nitrogen content	0.061
		Available phosphorus content	0.075
		Available potassium content	0.051
	Farmland management	Irrigation capacity	0.115
		Farmland shelterbelt	0.070
		Desertification degree	0.083

Table 2. Indicator weights for high-standard farmland construction suitability evaluation in Wensu County.

Target Layer	Subsystem Layer	Criterion Layer	Indicator Layer	Combined Weight
High-Standard Farmland Construction Suitability Evaluation	Construction suitability	Natural conditions	Topographic position	0.016
			Soil profile	0.048
			Slope	0.032
			Effective soil depth	0.064
		Soil nutrients	Organic matter content	0.06
			Available phosphorus content	0.036
			Available potassium content	0.024
		Infrastructure	Road accessibility	0.072
			Irrigation guarantee rate	0.12
			Farmland shelterbelt	0.048
		Sustainability	Salinization degree	0.168
			Contiguous farmland degree	0.112
	Spatial stability	Location conditions	Distance to transportation corridors	0.056
			Distance to urban areas	0.042
			Distance to Rivers	0.042
		Farmland characteristics	Farmland Nature	0.036
			Farmland utilization pattern	0.024

(1) Cultivated Land Quality (CLQ): Comprises 13 indicators across 4 criteria (site conditions, physicochemical properties, nutrients, and management) based on the GB/T33469-2016.

(2) High-Standard Farmland Construction Suitability (HSFCS): Comprises 17 indicators emphasizing construction suitability and spatial stability based on the GB/T30600-2022.

Indicator weights were determined using the Analytic Hierarchy Process (AHP), validated by expert consultation [46]. The specific indicators and their calculated weights are listed in Table 1 and Table 2.

Fuzzy Comprehensive Evaluation

To standardize indicators with different dimensions, the fuzzy comprehensive evaluation method was applied [1, 23]. The ridge-type and valley-type membership functions were constructed to normalize numerical indicators to the [0, 1] range, while conceptual indicators were quantified using the Delphi method. Detailed parameters for the membership functions are provided in Tables S1–S4 (Supplementary Materials).

The Comprehensive Index (IFI) for both CLQ and HSFCS was calculated using the weighted linear combination method [10, 23]:

$$IFI = \sum_{i=1}^{n} (W_i \times F_i)$$

Where *IFI* represents the comprehensive index; F_i denotes the membership degree of the i-th indicator; and W_i corresponds to the weight of the i-th indicator.

The classification standards for both systems were determined using the natural breakpoint method (Jenks). The detailed grading thresholds for CLQ and HSFCS are provided in Tables S5 and S6 (Supplementary Materials), respectively.

Future Prediction and Coupling Analysis

The Patch-generating Land Use Simulation (PLUS) model was employed to predict the spatial distribution of CLQ grades in 2031 [35]. The Land Expansion Analysis Strategy (LEAS) module extracted expansion probabilities based on 2015 and 2023 data (Fig. 3), and the CARS module simulated future landscape dynamics.

Coupling Coordination Degree Model

To quantify the interaction between CLQ and HSFCS, the Coupling Coordination Degree Model (CCDM) was adopted. The detailed calculation process follows established formulas [47, 48]:

$$D = \sqrt{C \times T},\ T = \alpha U_1 + \beta U_2$$

Where *D* is the coupling coordination degree; *C* is the coupling degree; *T* is the comprehensive coordination

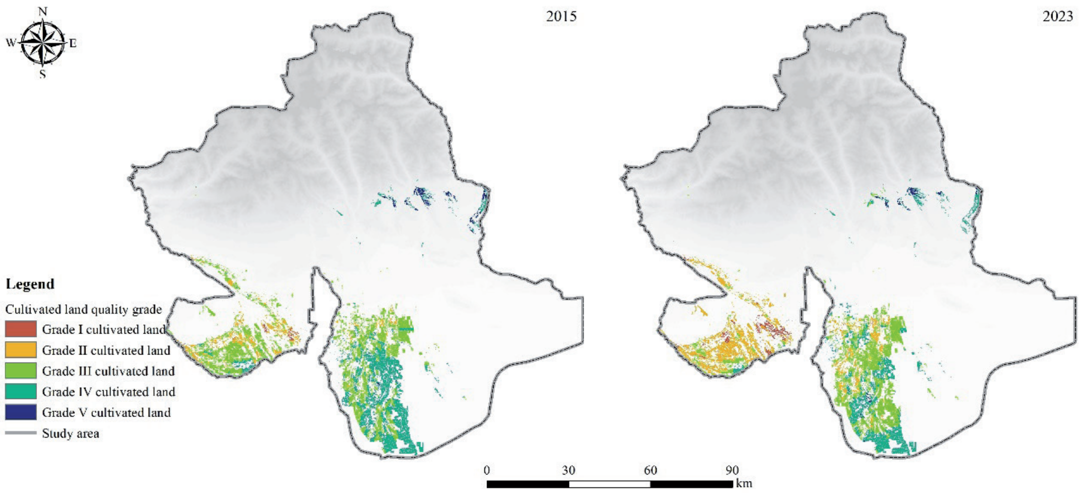

Fig. 3. Cultivated land quality classification maps of Wensu County in 2015 and 2023.

index; and U_1 and U_2 are the normalized evaluation scores of the CLQ and HSFCS systems, respectively. We set $\alpha = \beta = 0.5$, assuming equal importance for both systems.

Results

Evaluation and Prediction of Cultivated Land Quality Grade in Wensu County

Evaluation of Cultivated Land Quality Grades in Wensu County

The spatial distribution of Wensu County's 2023 cultivated land quality grade evaluation is shown in Fig. 3. The data show that among Wensu County's cultivated land quality grades in 2023, Grade III land has the largest area at 393.47 km^2, accounting for 38.15%; Grade V land has the smallest area at 19.46 km^2, accounting for 1.89%. According to the natural breakpoint method, the highest quality Grades I-II farmland were designated as high-quality land, with a total area of 349.60 km^2, accounting for 33.89% of the total county farmland; Grade III land was designated as medium-quality land, with an area of 393.47 km^2, accounting for 38.15%; Grades IV-V land were designated as low-quality land, with a total area of 288.45 km^2, accounting for 27.96%.

Prediction of Cultivated Land Quality Grades in Wensu County

This study used the PLUS model to simulate and generate Wensu County's 2031 cultivated land quality grades evaluation spatial distribution map (Fig. 4). Results show that in 2031, Grade II land will have the largest area at 385.83 km^2, accounting for 39.92%; Grade V land will have the smallest area at 10.21 km^2, accounting for 1.06%. According to the natural breakpoint method, the highest quality Grades I-II farmland were designated as high-quality land, with a total area of 405.40 km^2, accounting for 42.06% of the total county farmland; Grade III land was designated as medium-quality land, with an area of 284.14 km^2, accounting for 29.48%; Grades IV-V land were designated as low-quality land, with an area of 274.38 km^2.

Cultivated Land Quality Dynamic Change Analysis

Comparing the 2023 cultivated land quality grades with the simulated 2031 cultivated land quality grades shows that the county's cultivated land quality grades will show an overall improvement trend by 2031 (Fig. 5), with particularly significant grade improvements in medium-low grade farmland, and some low-quality farmland improving by one to two grades. From the specific changes (Table 3), among low-quality land,

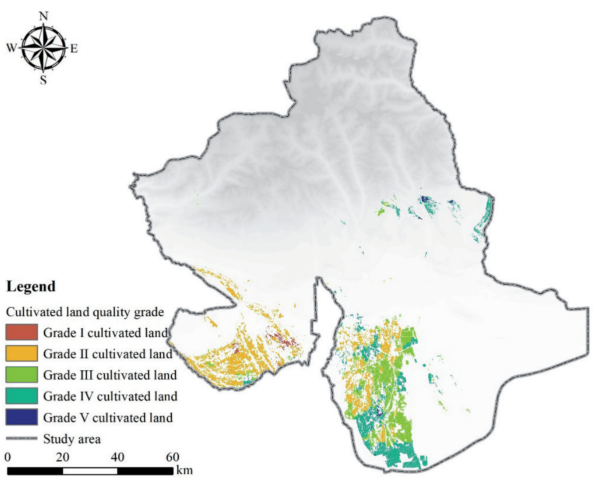

Fig. 4. PLUS model simulation of cultivated land quality classification in Wensu County for 2031.

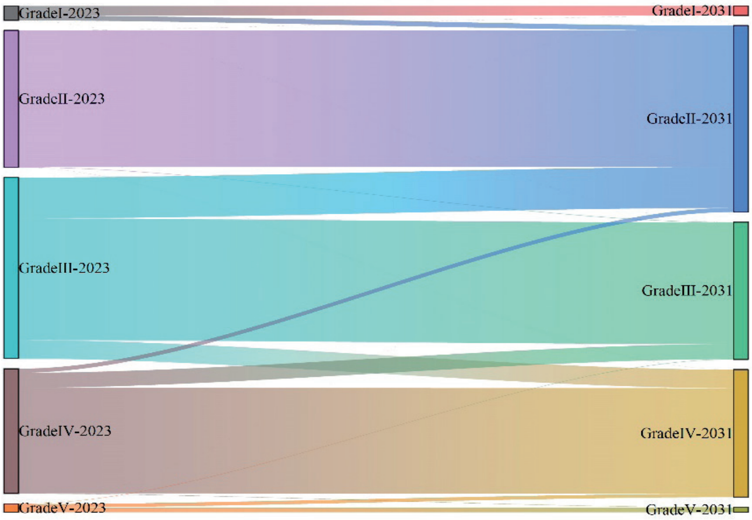

Fig. 5. Area changes of cultivated land quality grades in Wensu County from 2023 to 2031.

approximately 11.6% of farmland improved by one to two grades to become medium-quality land, covering 29.54 km^2; approximately 3.13% of low-quality land showed significant improvement to Grade II level, covering 7.97 km^2. Medium-quality land changes show fluctuation, with approximately 22.63% of medium-quality land significantly improving to high-quality land, covering about 78.47 km^2; approximately 10.3% of medium-quality land slightly declining to Grade IV, but no degradation to Grade V occurred. High-quality land maintained relatively high quality without significant changes.

Cultivated Land Quality Limiting Factors

This study analyzed the limiting factors for high, medium, and low-quality land in Wensu County, finding that salinization, organic matter, available phosphorus, irrigation capacity, and farmland shelter forest showed higher limitation degrees, mainly characterized by mild and moderate limitations. From regional perspectives, limiting factors show obvious differences: salinization limitations are mainly distributed in Qingquan Farm, Arele Town, Jiamul Forest Farm, Kezile Town, and other areas; organic matter limitations are mainly in Gulawati Township, Jiamu Town, Gongtuan Farm, and other areas; available phosphorus limitations are mainly in Tuohula Township, Gongtuan Farm, and other areas; irrigation capacity limitations are distributed in all regions; farmland shelter forest limitations are mainly in Youth Farm and Jiamu Town areas.

Evaluation of High-Standard Farmland Construction Suitability in Wensu County

Suitability Grade Division

This study calculated the Wensu County high-standard farmland construction suitability comprehensive index, obtaining a comprehensive index range of 0.52-0.92 with a mean value of 0.69. This indicates that Wensu County's high-standard farmland construction suitability comprehensive index is relatively high overall, but with regional differences. Using the natural breakpoint method, Wensu County high-standard farmland construction suitability was divided into six grades from high to low, with Grades I-VI corresponding to highly suitable, moderately

Table 3. Transition matrix of cultivated land quality grade areas in Wensu County from 2023 to 2031 (km^2).

2023 \ 2031	Grade I	Grade II	Grade III	Grade IV	Grade V	Total Area
Grade I	17.53	9.54	0.05	0	0	27.12
Grade II	0.15	259.56	0.73	0.17	0	260.61
Grade III	0.02	78.48	232.68	35.76	0	346.94
Grade IV	0	7.97	28.88	201.2	0.62	238.67
Grade V	0	0.02	0.66	6.63	8.73	16.04
Total Area	17.7	355.57	263	243.76	9.35	889.38

suitable, suitable, marginally suitable, less suitable, and unsuitable, respectively (Table 4).

From an area proportion perspective, 68.5% of Wensu County farmland is suitable for high-standard farmland construction, covering Grades I (highly suitable), II (moderately suitable), and III (suitable). This farmland is mostly high-quality land with not only high land capability but also a significant proportion of the county's farmland, serving as a core area for high-standard farmland construction. Another 21.92% of the farmland is in the marginal zone for high-standard farmland construction, mainly medium-quality land areas. For this farmland, key protection measures are needed to prevent farmland degradation and maintain current quality levels. The remaining 9.579% of the farmland belongs to the unsuitable areas for high-standard farmland construction, including Grade V (less suitable) and Grade VI (unsuitable). This farmland is mostly low-quality land with poor land capability and more prominent limiting factors, facing greater difficulties in management and construction, making it less suitable for high-standard farmland construction.

Spatial Distribution Characteristics

According to suitability evaluation results, Wensu County's high-standard farmland construction suitability grades show certain spatial characteristics based on natural conditions, soil nutrients, infrastructure, location conditions, and other evaluation indicators, as shown in Fig. 6. Wensu County's farmland is mainly divided into three major areas: southwestern, southeastern, and northeastern Wensu County. Among these, southwestern farmland accounts for about one-third of the total county farmland area, with relatively high cultivated land quality and a comprehensive index mean of 0.76. Most of the land belongs to high-quality land with relatively high construction suitability overall, showing a contiguous distribution of Grades I, II, and III, while Grades IV, V, and VI show a scattered distribution.

From the specific condition analysis, this area is mostly located in the middle alluvial-proluvial fan with sufficient effective soil depth, high irrigation guarantee rate, and farmland shelter forest level, good farmland leveling, mainly large field cultivation with

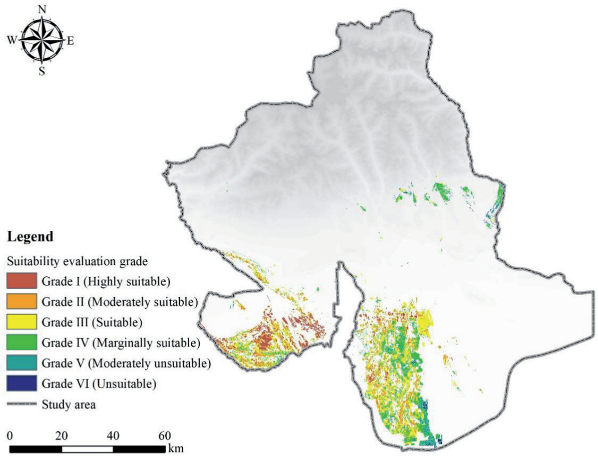

Fig. 6. High-standard farmland construction suitability map of Wensu County.

high mechanization degree. Additionally, being close to the Wensu County seat enables convenient access to technical support, providing a good foundation for high-standard farmland construction. Combined with the 2031 cultivated land quality grade simulation results, cultivated land quality in this area can be effectively guaranteed in the future with sustainable development capability, showing significant high-standard farmland construction suitability.

However, this area also contains some farmland with lower suitability, mainly concentrated in the southeastern corner of Arele Town. This farmland is constrained by topography, relatively far from towns with low transportation accessibility, while facing serious soil salinization problems with poor cultivated land quality that is difficult to improve rapidly in the near term.

Southeastern Wensu County farmland accounts for about 60% of the total county farmland area, being the most widely distributed area, but compared to the southwest, the overall evaluation index is lower with fewer Grade I (highly suitable) and Grade II (moderately suitable) farmland units, indicating relatively weak basic conditions for high-standard farmland construction.

Table 4. Suitability classification standards and area distribution for high-standard farmland construction in Wensu County.

Suitability Grade	Suitability Level	Comprehensive Index (IFI)	Area (km^2)	Area Percentage (%)
Grade I	Highly suitable	≥0.8	119.28	11.56%
Grade II	Moderately suitable	(0.75,0.8)	254.28	24.66%
Grade III	Suitable	(0.7,0.75)	332.95	32.28%
Grade IV	Marginally suitable	(0.65,0.7)	226.03	21.92%
Grade V	Moderately unsuitable	(0.6,0.65)	86.00	8.34%
Grade VI	Unsuitable	≤0.6	12.79	1.24%

Coupling Coordination Analysis of Cultivated Land Quality and High-Standard Farmland Suitability

To further explore the coordinated development level between high-standard farmland construction suitability evaluation results and cultivated land quality grade evaluation and prediction results, this study used a coupling coordination degree model for binary system coupling analysis. Results show that the spatial coupling degree performance is outstanding, with the spatial evaluation units having coupling degree > 0.7 accounting for over 80% in both 2023 and 2031 (Figs. 7a) and b)), showing strong spatial distribution consistency. Overall evaluation results of the coordination index for 2023 and 2031 show that spatial evaluation units > 0.5 account for over 60%, presenting "high west, low east" spatial differentiation characteristics (Figs. 7c) and d)). Overall evaluation results of the coupling

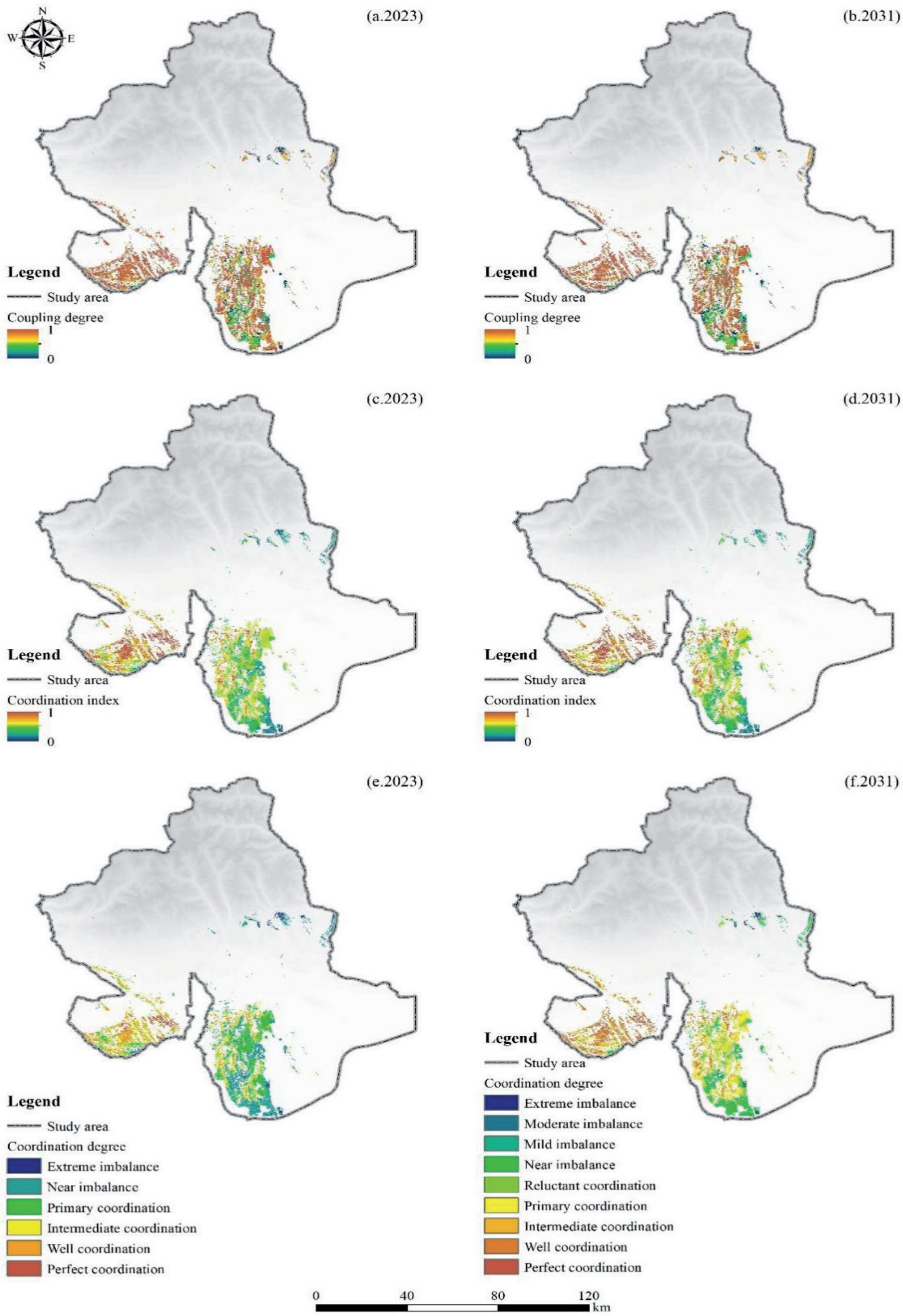

Fig. 7. Coupling coordination degree between cultivated land quality and high-standard farmland construction suitability in Wensu County.

coordination degree for 2023 and 2031 show that spatial evaluation units > 0.5 account for the absolute majority, with proportions exceeding 85%, occupying absolute dominance. Overall, high-standard farmland construction suitability evaluation results and cultivated land quality grade evaluation results are in a good collaborative development state with a high coordination degree and interdependence, indicating that cultivated land quality and high-standard farmland construction suitability have formed relatively high-level matching relationships.

Table 5 shows the changes in farmland area distribution corresponding to different coupling coordination degree grades. The data show that in 2023 and 2031, near-imbalance, primary coordination, and good coordination grades consistently dominate Wensu County farmland: 2023 total area reached 798 km^2, accounting for 77.46%; 2031 total area was 688 km^2, accounting for 71.48%. The intermediate coordination grade is in a secondary position, with the 2023 area of 176.28 km^2, accounting for 17.11%; the 2031 area slightly decreased to 174.81 km^2, with the proportion slightly rising to 18.15%. Other coordination grades account for less than 10%, in weak positions within the overall structure. Combined with Fig. 7, coupling coordination degree values between cultivated land quality grades and high-standard farmland construction suitability grades are highly consistent with coordination index spatial distribution characteristics, both showing "high west, low east" spatial patterns with primary coordination and good coordination as dominant types.

In summary, the quantitative results reveal a clear "high-west, low-east" spatial gradient governing the Wensu oasis. Specifically, the southwestern region exhibits a benign resonance, where high cultivated land quality (Grades I-II) and construction suitability overlap significantly, resulting in a coupling coordination degree exceeding 0.5 across 85% of the study area. In these high-coordination zones, land quality management effectively boosts high-standard farmland grades. Conversely, the southeastern region faces a structural mismatch, where the spatial correlation weakens significantly due to the dual constraints of low land quality (Grades IV-V) and high salinization risks. This indicates that while the overall coordination level is high, the "lagging" southeastern areas require targeted optimization strategies to break the current developmental bottleneck.

Discussion

Driving Mechanisms and Ecological Trade-offs in Farmland Quality Evolution

This study reveals a divergent evolutionary pattern of farmland quality in Wensu County, characterized by "overall improvement with localized risks". This process is profoundly governed by the specific "water-soil-salt" multi-constraint mechanism inherent to arid oases [4, 49]. First, the significant expansion of Grade II land (a 36.4% increase by 2031) robustly confirms the yield-enhancing efficacy of modern agricultural technologies in arid regions. Evidence indicates that the promotion of high-efficiency water-saving irrigation (e.g., mulched drip irrigation) and soil amendment techniques can effectively optimize the hydrothermal-saline environment in the root zone, thereby boosting productivity in medium- and low-yield fields by 15%-20% [23]. This demonstrates the effectiveness of current quality enhancement strategies. Second, the slight contraction of prime farmland area (from 27.12 km^2 to 17.7 km^2) signals a critical ecological vulnerability. This aligns with the "Mountain-Oasis-Desert" system's fragility theory, which suggests that top-tier oasis farmland, despite occupying optimal niches for water and soil resources, remains highly susceptible to anthropogenic disturbances from intensive development. This finding underscores that the management of premium farmland must evolve beyond

Table 5. Cultivated land area distribution by coupling coordination levels and quality grades in Wensu County (km^2).

Coordination Level	High-quality (I-II)				Medium-quality (III)		Low-quality (IV-V)			
	I		II		III		IV		V	
Time	2023	2031	2023	2031	2023	2031	2023	2031	2023	2031
Extreme imbalance	<0.01	<0.01	<0.01	0.11	2.28	4.24	9.25	14.05	18.22	9.27
Mild imbalance	<0.01	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	0.55	<0.01	0.25
Near imbalance	<0.01	<0.01	1.51	0.92	30.26	26.37	259.74	211.02	<0.01	0.26
Barely coordinated	<0.01	<0.01	<0.01	4.96	<0.01	29.78	<0.01	21.88	<0.01	<0.01
Primary coordination	<0.01	<0.01	23.43	41.47	261.99	183.40	<0.01	15.99	<0.01	<0.01
Intermediate coordination	1.52	0.82	75.81	133.69	98.95	40.30	<0.01	<0.01	<0.01	<0.01
Good coordination	7.48	4.15	213.61	204.68	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Excellent coordination	26.23	14.60	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01

mere productivity enhancement toward a paradigm of "maintaining productivity while preserving ecological buffers" [7, 42], preventing secondary salinization or soil compaction caused by overexploitation.

Spatially Differentiated "Geological-Hydrological" Logic for Suitability

The suitability for high-standard farmland construction exhibits a distinct spatial gradient of "high in the southwest and low in the southeast", which fundamentally reflects the spatial heterogeneity of regional geomorphology and hydrological conditions. The southwest's advantage stems from its prime location within the central alluvial-proluvial fan, where deep soil profiles (80-120 cm) and high irrigation reliability (> 90%) create an optimal soil-water configuration, resulting in a high suitability index average of 0.76. This quantitatively validates the "natural conditions priority" principle outlined in the High-Standard Farmland Construction Guidelines [50]. Conversely, constraints in the southeast are primarily attributed to salinization bottlenecks. Situated at the intersection of the groundwater overflow zone and the highly evaporative Gobi Desert plain, this area features shallow soil layers and high salinity (1.5-2.5 $g \cdot L^{-1}$), resulting in lower suitability indices (0.55-0.65). By assigning a high weight (16.8%) to the salinization factor (Table 2), this study quantitatively confirms that salt regulation is the prerequisite for high-standard farmland construction in this region [4, 10]. This implies that in marginal oasis zones with low suitability, conventional engineering interventions alone are unlikely to be effective; addressing the fundamental constraint of salinization must be prioritized.

Synergistic Feedback and Differentiated Strategies in the "Quality-Suitability" Binary System

The coupling coordination analysis further elucidates the interactive mechanisms between farmland quality and construction suitability. In the high-coordination zone (southwest), the spatial overlap between high-quality farmland and high-suitability areas exceeds 85%, establishing a positive feedback loop where improved infrastructure enhances farmland quality, which in turn boosts construction suitability. This virtuous cycle is underpinned by the region's well-developed irrigation network and low risk of salinization. In the low-coordination zones (southeast, coupling coordination < 0.5), the imbalance stems primarily from the lag in salinization control. This finding provides micro-scale empirical evidence for the farmland conservation in arid regions: enhancing coordination requires an integrated "engineering-agronomic-biological" approach rather than isolated measures [17, 41]. Consequently, differentiated management strategies are recommended: for the high-coordination zone in the southwest, priority should be given to upgrading high-standard farmland and developing smart agriculture; for the low-coordination zone in the southeast, the blind pursuit of construction scale must be avoided. Instead, biological drainage and soil improvement projects should be prioritized, with high-standard farmland construction implemented sequentially only after baseline resource and environmental conditions have improved.

Research Limitations and Outlook

This study has two limitations requiring further refinement. First, regarding the simulation mechanism: the PLUS model, which relies on "trend extrapolation" from historical data, struggles to accurately capture nonlinear abrupt changes driven by strong policy interventions (e.g., "determination of land based on water availability"), potentially leading to conservative future scenario projections [38]. Second, regarding evaluation dimensions: due to data constraints, this study focused on assessing natural endowments while insufficiently considering micro-socioeconomic factors, such as farmers' willingness to operate and the marginal benefits of engineering investments. This neglects the influence of micro-level decision-making on project implementation. Future research could explore the construction of a "macro-pattern-micro-behavior" coupled model by incorporating Multi-Agent Systems (MAS) to simulate farmers' policy response mechanisms. Furthermore, integrating CMIP6 climate scenario data could deepen the understanding of long-term stress mechanisms on oasis farming systems caused by extreme droughts and the water resource fluctuations, providing more forward-looking support for agricultural resilience management in arid regions [2].

Conclusions

This study established an integrated "Quality Evolution-Suitability Evaluation-Coupling Coordination" framework to quantify the dynamic relationships between cultivated land quality and high-standard farmland construction in Wensu County. The main conclusions are:

(1) A deterministic upgrading trend in cultivated land quality was identified. In 2023, the quality exhibited a "Grade III dominance (38.15%)" and a mosaic pattern. By 2031, a significant structural optimization is projected, with Grade II land expanding to 385.83 km^2 (36.4% increase) to become the dominant category (39.92%), while low-quality land decreases to 274.38 km^2. This trajectory quantitatively validates the long-term efficacy of current soil improvement and water-saving irrigation policies in the region.

(2) High-standard farmland suitability displays distinct spatial heterogeneity. The suitability index exhibits a "Southwest-High, Southeast-Low" gradient (mean 0.69). Highly suitable areas (Grades I-III) cover

68.5% of the farmland, primarily clustered in the southwestern alluvial fans where soil-water conditions are optimal (soil depth 80-120 cm). Conversely, the southeast is identified as a marginal zone constrained by salinization (1.5-2.5 $g \cdot L^{-1}$) and fragmentation, rendering 9.58% of the area unsuitable for immediate large-scale construction.

(3) The binary system maintains a high level of coupling coordination. Areas with a coupling coordination degree > 0.5 cover 85% of the study region, establishing a stable collaborative pattern. However, a structural lag persists in the southeast. Simulation results indicate that targeted salinization control and irrigation facility upgrading in these lagging zones could enhance the regional coordination degree by 15%-20%, serving as the key pathway for systemic improvement.

In summary, this research provides a transferable quantitative tool for arid oasis farmland management. The findings offer scientific support for "differentiated layout" strategies along the Belt and Road Initiative, emphasizing that balancing food security with ecological stability requires prioritizing natural endowments and addressing salinity bottlenecks.

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Conflict of Interest

The authors declare no conflict of interest.

AI Usage Disclosure Statement

During the preparation of this manuscript, the authors used Google Gemini Pro solely for English language polishing, grammar checking, and improving readability. The tool was not used for research design, data generation, data processing, statistical or spatial analysis, figure preparation, result interpretation, or conclusion generation. All AI-assisted language edits were reviewed, revised, and verified by the authors. The authors take full responsibility for the accuracy, integrity, originality, and final content of the manuscript.

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Supplementary Materials

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