RESEARCH ARTICLE

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Digital-Intelligence Assessment of Production–Living–Ecological Spaces for Agricultural Modernization: A Case Study of Ulanqab City

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Abstract

Against the backdrop of the synergistic advancement of rural revitalization and agricultural modernization, optimizing the Production-Living-Ecological (PLE) spatial pattern and introducing digital-intelligent technologies have become key pathways for enhancing sustainable rural development capabilities. This study takes Ulanqab City in Inner Mongolia, a typical agro-pastoral ecotone, as a case study. Based on multi-source remote sensing image data from 2000 to 2020, it comprehensively utilizes a coupling coordination model and spatial information technology to evaluate the evolution characteristics of its PLE spaces and the coordination mechanisms of agricultural functions, supplemented by NDVI and soil moisture data to link ecological and agricultural functions. The results indicate that the city's PLE spaces exhibit a pattern of "North-South differentiation, overall coordination," temporally evolving through three stages: "maladjustment-breaking-in-differentiation." The southern region promotes PLE synergy and urban-rural integration leveraging clean energy and smart logistics; the central region maintains functional balance through the Grain for Green program and characteristic eco-agriculture; the northern region is constrained by traditional animal husbandry and ecological degradation. Addressing regional disparities, differentiated pathways are proposed: developing "smart agriculture + digital supply chains" in the south, constructing an "ecological–intensive" intelligent animal husbandry model in the north, and establishing a remote sensing and Internet of Things (IoT) based value realization mechanism for eco-agriculture in the central region. Recommendations include enhancing agricultural digitalization levels and PLE functional coordination through spatial regulation, green technology empowerment, and ecological compensation policies, providing theoretical and data support for achieving sustainable agricultural development and modernized rural revitalization.

Keywords: production-living-ecological (PLE) spaces, digital intelligence, agricultural modernization, coupling coordination model, Ulanqab City.

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1 Introduction

Rural "Production-Living-Ecological" (PLE) spaces refer to production, living, and ecological spaces [1, 2]. The evolution of their patterns and the optimization of their functional coordination [3] directly impact agricultural productivity [4, 5] and constitute an important foundation for achieving agricultural modernization and rural revitalization. Particularly in the current context of rapid development in digital agriculture and smart rural planning, how to enhance agricultural production efficiency [6, 7], rural living quality, and ecological restoration capacity [8] through spatial digitalization has become a frontier topic in interdisciplinary research spanning human-economic geography and agricultural information science. PLE spaces are the product of the coupling of natural and socio-economic systems [9]. Their evolution mechanisms are complex, involving multiple dimensions such as resource allocation, industrial transformation, and ecological restoration. The agro-pastoral ecotone, as an important ecological barrier and ecologically fragile zone in northern China, is a significant component of human-land relationship research [10, 11]. Currently, research on Production-Living-Ecological (PLE) spaces predominantly focuses on urban functional zoning and urban-rural gradient differences. For instance, studies such as Cattivelli et al.'s [12] analysis of PLE space identification in urban-rural territorial systems, and Wang et al.'s [13] investigation into the evolution characteristics of PLE space conflict patterns in metropolitan rural areas, are predominantly centered on the functional assessment of urban and rural PLE spaces. However, research targeting the agro-pastoral ecotone—a typical ecological-production sensitive area—remains relatively scarce. This study concentrates on the assessment of PLE space functions for agricultural modernization within the context of the typical agro-pastoral ecotone in Ulanqab City. It directly links the PLE space assessment with the goals of agricultural modernization, thereby highlighting the guiding role of agriculture within the PLE functions.

Furthermore, Ulanqab City, as a typical representative of the northern agro-pastoral ecotone, features a fragile ecosystem and traditional agricultural production methods. The layout of public living spaces directly impacts cultivated land use efficiency, grassland ecological restoration, and water resource management effectiveness [14]. There is an urgent need to enhance the synergy level of Production-Living-Ecological (PLE) spaces through smart agricultural technologies, thereby promoting the deep integration of agricultural modernization and rural revitalization. However, existing research on agricultural functions predominantly relies on traditional statistical identification and is gradually expanding toward intelligent assessment and simulation decision-making [15]. Studies in digital agriculture [16], precision agriculture [17], and smart rural planning [18] are still in their early stages. According to the rural territorial system theory proposed by Liu et al. [19], it is essential to coordinate PLE functions to foster intensive, livable, and green collaborative development. Lin et al. [20] systematically summarized research progress on PLE spaces in territorial spatial optimization, emphasizing the importance of digital and intelligent technologies in spatial governance. For example, crop monitoring based on UAV remote sensing [21], IoT-based smart irrigation systems [22], and smart agricultural big data decision support platforms [23] all provide innovative technological pathways for PLE space optimization. Therefore, this study, based on multi-source remote sensing image data and integrating NDVI and soil moisture data to link ecological and agricultural functions, employs a coupling coordination model for intelligent assessment. It analyzes the evolution of the PLE spatial pattern and the coordination mechanisms of agricultural functions in Ulanqab City, aiming to provide a digital scientific basis and intelligent decision support for precision agriculture, smart rural planning, and ecological monitoring.

2 Study Area

Located in the far north of China and in the central part of the Inner Mongolia Autonomous Region, Ulanqab City is a prefecture-level city administered by the Autonomous Region. It borders Hebei Province to the east, Xilingol League to the northeast, Shanxi Province to the south, Hohhot, the regional capital, to the southwest, Baotou City to the northwest, and Mongolia to the north (see Figure 1). The city's land cover consists of approximately 23.1% cultivated land, 42.7% grassland, and 18.5% forestland. The region's average annual precipitation ranges from 150mm to 450mm, characterized by ecological vulnerability coexisting with relatively lagging economic development. Strategically, Ulanqab City serves as a key gateway for Inner Mongolia's connections eastward and westward. It functions not only as a transportation hub linking the North China, Northeast China, and Northwest China economic zones but also as a significant international corridor connecting China to Mongolia, Russia, and Eastern European countries.

3 Construction and Assessment of Rural PLE Function Indicators

Against the backdrop of the deep integration of agricultural modernization and digital-intelligent technologies, the assessment of rural Production-Living-Ecological (PLE) spatial functions has shifted from traditional qualitative descriptions toward intelligent digital evaluation driven by multi-source remote sensing data to support agricultural functions. This study takes Ulanqab City—a typical agro-pastoral ecotone in northern China—as a case study. By integrating multi-source remote sensing imagery with a coupling coordination intelligent model, and supplementing with NDVI and soil moisture data to link ecological and agricultural functions, we construct an intelligent evaluation system encompassing production, living, and ecological functions. The approach emphasizes the capacity for digital assessment of agricultural functions, transcends the limitations of traditional PLE spatial pattern descriptions, and achieves an intelligent advancement from spatial qualification to functional coupling.

3.1 Connotation of PLE Functions and Orientation for Agricultural Digital-Intelligent Assessment

Rural areas, as territorial complexes integrating natural, social, and economic characteristics, fulfill multiple functions including production, living, and culture [24], with agriculture and related industries constituting their primary activities [25]. Their production function is manifested through the supply of agricultural products [26] and the capacity to drive non-agricultural industries [27]. The living function focuses on public welfare, the fulfillment of communal needs, and the level of infrastructure [28]. The ecological function pertains to resource carrying capacity and environmental quality [5, 29]. In the context of digital agriculture and smart rural development, the assessment of Production-Living-Ecological (PLE) functions must not only reflect static spatial patterns but should also dynamically evaluate the synergistic and competitive relationships between these functions through intelligent technological means such as remote sensing retrieval and GIS spatial analysis [30]. This provides quantifiable and simulatable decision-making support for agricultural modernization. This study emphasizes a "digital intelligence" methodological orientation, aiming to achieve intelligent assessment of PLE functions through the integration of multi-source remote sensing data and model coupling.

3.2 Construction of a Digitally Intelligent PLE Function Indicator System

Based on the characteristics of the typical agro-pastoral ecotone in Ulanqab City and incorporating the "Production-Living-Ecological" (PLE) land use classification system [31], this study constructs a digital-intelligent evaluation indicator system encompassing the three major functions of production, living, and ecology. Building upon traditional evaluation methods, it enhances the integration of remote sensing and ground monitoring data, deliberately introduces NDVI and soil moisture indicators to link ecology and agriculture, and connects ecological quality with agricultural production potential through digital-intelligent means, thereby improving the timeliness and accuracy of the assessment.

3.2.1 Production Function Indicators

The production function refers to the capacity of the agricultural system to provide agricultural products for humans [32]. Its sustenance necessitates land input, with the physical measure being the planted area [33], and the final output measure being the harvested area [34]. Therefore, this study selects remote sensing imagery depicting the harvested areas of four typical crops-corn, rice, wheat, and soybeans-for the years 2000 and 2020 for digital-intelligent analysis.

Comparison of Figures 2 and 3 reveals that over the ten-year period, the corn harvested area increased by 106%, while the areas of all other crops showed declining trends. This indicates that socio-land resources are being reallocated toward corn production, reflecting a sharp intensification of its production function. Conversely, the imagery for wheat shows its distribution transitioning from contiguous patterns to fragmented patches, with a 61% reduction in area. This signifies a notable contraction of its production function, yielding predominance to other functions (such as ecological functions). Changes in crop harvested area are driven by fundamental factors including economic benefits, policy orientation, and ecological constraints. These shifts more profoundly reveal the long-term evolutionary trends and the essential nature of

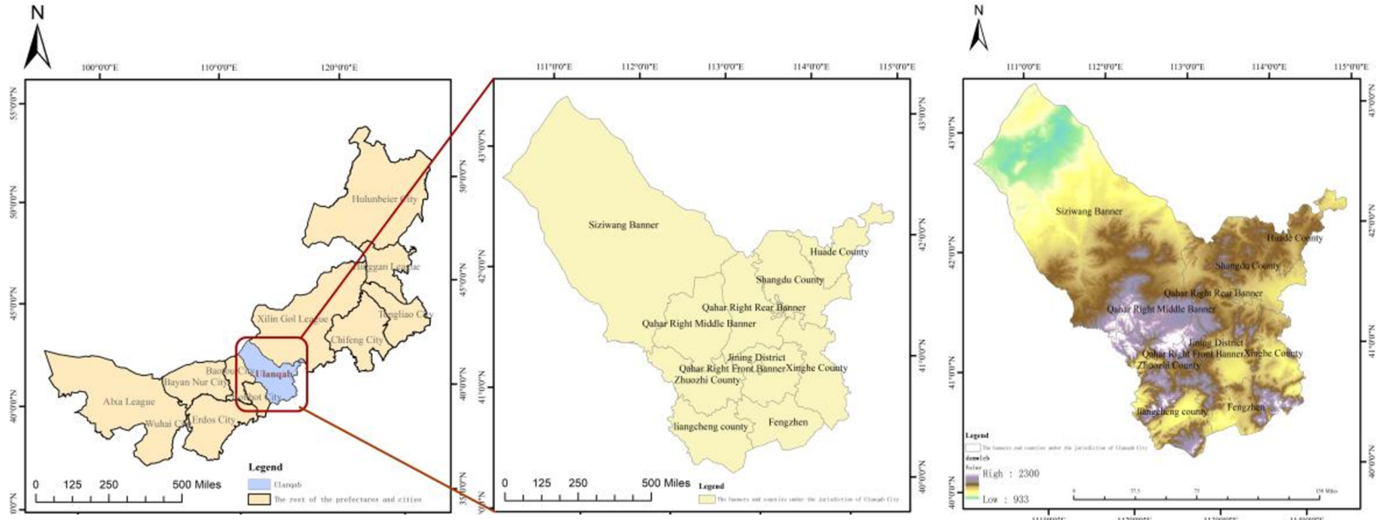

Figure 1. Location and topography map of Ulanqab City [46].

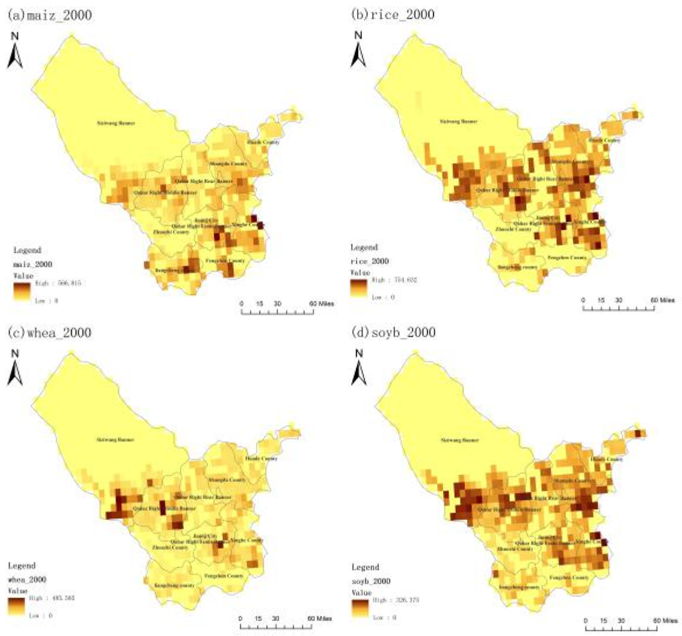

Figure 2. Harvested area (Hectares) of Corn, Rice, Wheat, and Soybeans in Ulanqab City, 2000 [47].

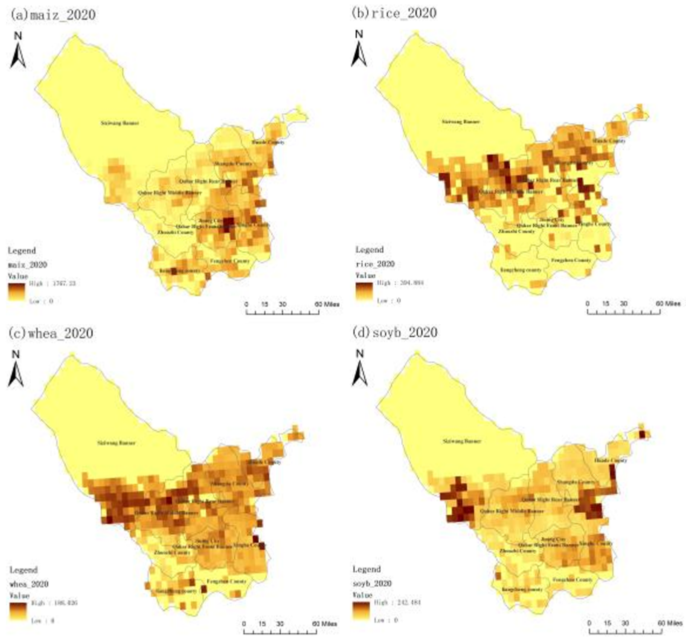

Figure 3. Harvested area (Hectares) of Corn, Rice, Wheat, and Soybeans in Ulanqab City, 2020 [47].

structural adjustments within the agricultural "production function."

3.2.2 *Living Function Indicators*

This study employs nighttime light remote sensing data as the primary quantitative indicator of the living function, aiming to address the limitations of traditional statistical data in spatiotemporal continuity. An analysis of nighttime light data for Ulanqab City in 2000, 2005, 2015, and 2020 (see Figure 4) shows that the intensity of the living function exhibits a characteristic pattern of initial growth followed by stabilization. From 2000 to 2005, the light intensity peaked (with a DN value of 62) within five years, then slightly declined and stabilized. Spatially, the lights are highly concentrated in central urban areas like Jining District, with a pattern of slight enhancement in the light clusters at banner/county seats. This dynamic is not an isolated spatial pattern but a direct "manifestation" of regional socio-economic activities: changes in light intensity are strongly correlated with urbanization level, economic activity intensity, and population agglomeration, thereby successfully operationalizing the abstract concept of "living function" into a measurable spatiotemporal sequence.

The digital assessment of the living function provides

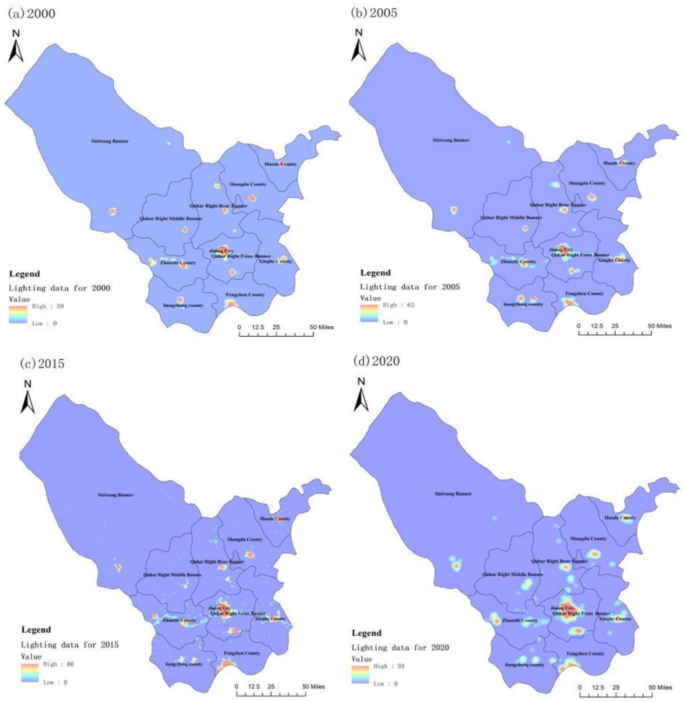

Figure 4. Nighttime light images of Ulanqab City for 2000, 2005, 2015, and 2020 [48].

crucial mutual verification of the "human-land relationship" for the concurrent transformation of agricultural functions. Specifically, the structural transformation revealed by agricultural function analysis—the "drastic shrinkage of labor-intensive crop (wheat) area [35, 36]" alongside the "expansion of mechanized crop (corn) [37] area"—necessarily released rural labor force towards urban spaces with stronger living functions. The stabilization and slight increase of light clusters at banner/county seats, as shown by the nighttime light data, constitute the spatialized and digitized evidence of this population redistribution process.

Therefore, the light data not only delineates the static pattern of the living function but also, through its dynamic changes, reveals the underlying social dynamics—such as labor migration and shifts in livelihood strategies—behind the transformation of agricultural functions. This achieves a "digital assessment from the living dimension" of changes in agricultural functions, thereby integrating the co-evolution of the production and living system functions into a unified explanatory framework.

3.2.3 Ecological Function Indicators

This study selects the Normalized Difference Vegetation Index (NDVI) and soil moisture as core indicators for the ecological function. These respectively represent vegetation cover vitality and soil hydrological conditions, jointly revealing the structure and functional evolution of the ecosystem. Analysis of time-series data from 2000-2020 for Ulanqab City indicates that its ecological function has undergone a significant "qualitative change."

An analysis of three-phase NDVI imagery for Ulanqab City (2000, 2010, and 2020; see Figure 5) indicates that its ecological function underwent a positive evolutionary process characterized by significant improvement followed by sustained performance at a high level. Specifically, the regional maximum NDVI value jumped from 0.3085 in 2000 to 0.6090 in 2010 and stabilized at the high level of 0.6034 in 2020. Concurrently, the low NDVI values also decreased from near 0 to negative and then recovered, indicating a widespread and substantial improvement in vegetation coverage and vitality across the area. This dynamic is not merely a display of vegetation spatial patterns but a direct digital representation of enhanced capacities for windbreak and sand fixation, soil and water conservation, and biodiversity maintenance, signifying a strengthened ecological function.

The digitally-evolved linkage between NDVI and agro-ecological functions provides a dual explanation of internal "driving force" and "constraining force" for the transformation of agricultural functions. Firstly, the sharp increase in NDVI between 2000-2010 highly coincides with the intensive implementation period of ecological policies like the "Grain for Green" program. This, from the perspective of a driving force, directly explains why the wheat harvested area shrunk drastically by 61.3% during the same period – namely, low-benefit marginal farmland actively withdrew from the agricultural production function to serve stronger ecological functions [38, 39]. Secondly, the maintenance of high NDVI values and stabilization after 2010 set an ecological constraint "ceiling" for agricultural function. It indicates that further agricultural expansion (e.g., the 106.6% increase in corn area) must occur within the boundaries of this ecological restoration achievement, thereby directing agricultural development towards internal structural adjustment and intensification, such as concentrating advantageous crops in areas with better water and soil conditions, rather than relying on extensional expansion by reclaiming ecologically fragile land. This ecological constraint also partly explains why the rice area could only increase modestly by 11.4%, as its expansion is strictly limited by water resources and ecological redlines. The time-series analysis of NDVI data successfully elevates the ecological

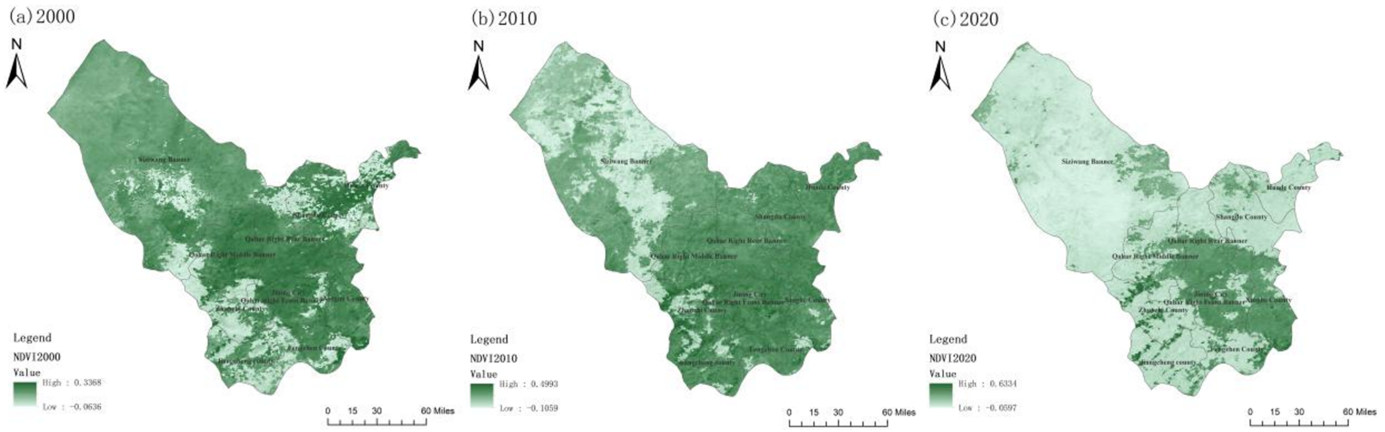

Figure 5. NDVI imagery of Ulanqab City for 2000, 2010, and 2020 [49].

function from a traditional spatial pattern description to an active, quantifiable explanatory variable in the digital assessment of agricultural functions. It not only confirms the ecological policy drivers behind agricultural structural adjustment but also reveals that the transformed agricultural production pattern is an optimized result formed under the constraints of a new environmental capacity characterized by significantly enhanced ecological function, thereby achieving a deeper, ecosystem-level digital assessment of agricultural function evolution.

Soil moisture is a key indicator for characterizing regional hydrothermal balance and ecological regulation functions [40], and its dynamics provide critical insights into the ecological context and resource constraints of agricultural transformation. Analysis of three-phase soil moisture data for Ulanqab City (2000, 2010, and 2020; see Figure 6) reveals that its ecological function underwent substantial changes, transitioning from extreme aridity to marked improvement, followed by relative stability. Specifically, the regional maximum soil moisture value surged from an extremely low 0.05 in 2000 to 0.32 in 2010, remaining at a high level of 0.30 in 2020. This order-of-magnitude increase, far exceeding the range of natural fluctuation, clearly indicates a fundamental improvement in regional-scale eco-hydrological conditions. It serves as direct digital evidence of the enhancement of ecological regulation functions such as soil water retention capacity and climate regulation.

This quantified evolution of ecological function provides a crucial perspective of "changing resource base" and an early warning of "sustainability risk" for the digital transformation of agricultural functions. Firstly, the significant improvement in soil moisture between 2000-2010 highly coincides with the implementation period of large-scale ecological projects like the Grain for Green Program. The increased vegetation coverage resulting from ecological restoration (corroborated by NDVI data) effectively reduced soil water evaporation and enhanced water conservation capacity. This, from the perspective of an improving resource base, provided potential moisture condition support for the expansion of high water-consumption crops like corn after 2010. However, the more critical assessment lies in revealing its inherent constraints and risks. Comparing the 2020 soil moisture (0.30) with that of 2010 (0.32) reveals a slight decreasing inflection point trend. This subtle change highly overlaps temporally with the peak expansion of corn planting area (+106.6%), strongly suggesting that the drastic agricultural restructuring, particularly the large-scale cultivation of high water-consumption corn, may have already begun exerting consumptive pressure on regional soil water resources, offsetting some of the gains brought by ecological restoration.

Therefore, the time-series analysis of soil moisture data elevates the ecological function from a static background description to a core criterion for dynamically assessing the sustainability of agricultural function transformation. It indicates that while agriculture in Ulanqab City benefits from the dividend of ecological improvement, it also faces new resource bottlenecks. The transformation of agricultural function from inefficient wheat to efficient corn, while economically successful, strongly depends for its long-term maintenance on the fragile water balance created by ecological restoration. The changing trend of soil moisture provides an advanced, quantified early warning of the ecological costs of this round of agricultural transformation and potential future water resource risks. Consequently, future

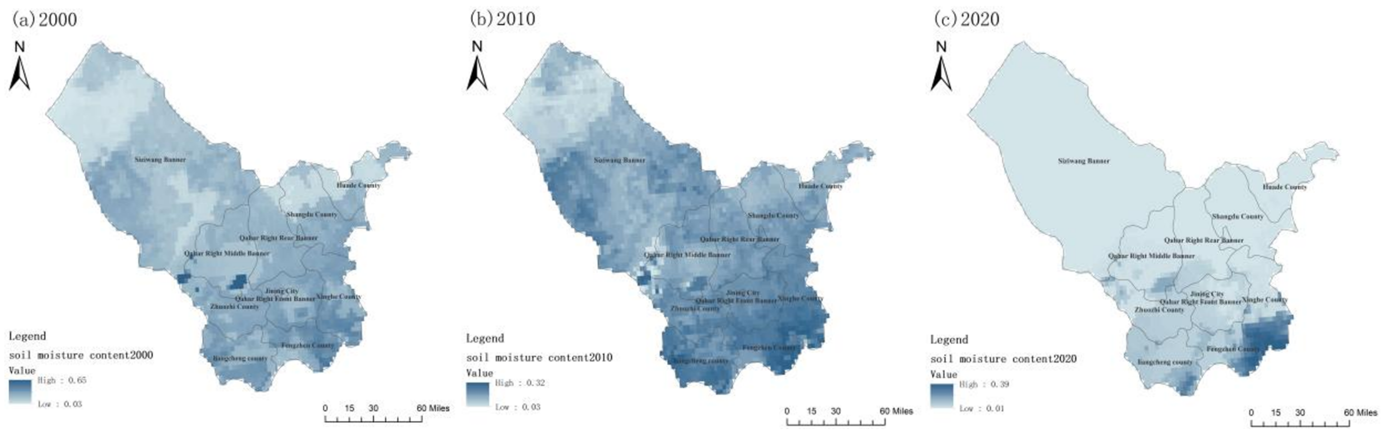

Figure 6. Soil moisture images of Ulanqab City for 2000, 2010, and 2020 [50].

agricultural development must shift from a model of "trading ecology for benefits" to a refined ecological model focused on "promoting sustainability through efficiency, " thereby achieving a truly digital and sustainable assessment.

NDVI and soil moisture showed a synergistic surge between 2000 and 2010, with NDVI increasing from 0.31 to 0.61 and soil moisture rising from 0.05 to 0.32, confirming the fundamental improvement in system functions resulting from ecological restoration projects. Between 2010 and 2020, while NDVI remained high, soil moisture showed a slight declining inflection point, indicating pressures on the ecosystem after reaching a new equilibrium. This dynamic assessment goes beyond static spatial pattern descriptions, providing a digital explanation at the mechanistic level for agricultural function transformation: the enhancement of ecological function serves both as a key driver phasing out inefficient agriculture like wheat cultivation and establishes rigid resource constraints for efficient agriculture like corn expansion. Simultaneously, its evolutionary trend provides an early warning about the long-term sustainability of agricultural models. Therefore, this indicator system achieves an advancement from describing ecological manifestations to linking internal mechanisms, establishing a solid quantitative foundation for understanding the ecological drivers and constraints of agricultural function transformation.

3.3 Digital Assessment of PLE Functions

The coupling and coordination of rural Production-Living-Ecological (PLE) functions constitute a systematic, dynamic, and regionally balanced process. Drawing upon existing research, a coupling coordination degree model for production, living, and ecological functions has been constructed [41, 42]. The specific calculation formulas are as follows.

1. Measurement of rural production (P)-living (L)-ecological (E) function coupling degree (C_{ple}):

$$C_{ple} = \left[\frac{F_p \times F_l \times F_e}{\left(\frac{F_p + F_l + F_e}{3} \right)^3} \right]^{1/3}$$

2. Measurement of rural production-living, production-ecological, and living-ecological function coupling degrees (C_{pl}, C_{pe}, C_{le}):

$$C_{pl} = \left[\frac{F_p \times F_l}{\left(\frac{F_p + F_l}{2} \right)^2} \right]^{1/2}$$

$$C_{pe} = \left[\frac{F_p \times F_e}{\left(\frac{F_p + F_e}{2} \right)^2} \right]^{1/2}$$

$$C_{le} = \left[\frac{F_l \times F_e}{\left(\frac{F_l + F_e}{2} \right)^2} \right]^{1/2}$$

3. Measurement of rural production-living-ecological function coupling coordination degree (D_{ple}):

$$D_{ple} = \sqrt{C_{ple} \cdot T_{ple}}$$

where:

$$T_{ple} = aF_p + bF_l + cF_e$$

4. Measurement of rural production-living, production-ecological, and living-ecological function coupling coordination degrees (D_{pl}, D_{pe}, D_{le}):

$$D_{pl} = \sqrt{C_{pl} \cdot T_{pl}}$$
$$D_{pe} = \sqrt{C_{pe} \cdot T_{pe}}$$
$$D_{le} = \sqrt{C_{le} \cdot T_{le}}$$

where:

$$T_{pl} = aF_p + bF_l,$$
$$T_{pe} = aF_p + cF_e,$$
$$T_{le} = bF_l + cF_e.$$

In the formulas, a, b, and c are undetermined coefficients of rural production, living, and ecological functions, respectively. Based on the interrelationships among production, living, and ecology and referring to relevant research [43], the undetermined coefficients are set as $a = 0.40$, $b = 0.30$, $c = 0.30$.

To evaluate the degree of interconnection among PLE functions, the coupling degree (C) values calculated from the above formulas are classified into four categories as shown in Table 1. This classification provides a framework for understanding the level of synergy and interaction between production, living, and ecological functions in rural areas.

Furthermore, to assess the overall balanced development level of PLE functions, the coupling coordination degree (D) is calculated and classified into six categories as presented in Table 2. This classification not only indicates the coordination status but also provides targeted optimization suggestions for different coordination levels.

3.4 Digital-Intelligent Assessment of "Production-Living-Ecological" Spaces

Production space primarily corresponds to cultivated land, living space mainly comprises built-up areas, and ecological space encompasses natural ecological land such as forests, shrublands, grasslands, water bodies, and barren land. Based on four phases of land-use remote sensing imagery from 2000 to 2020 (see Figure 7), and using remote sensing interpretation combined with GIS spatial overlay analysis, the results indicate that the land-use pattern in Ulanqab City is characterized by overall stability, with local optimization of cultivated land, point-like expansion of built-up areas, and structural adjustments in ecological land. This spatial configuration reflects the combined influence of ecological policies and urbanization processes.

Analysis reveals that the evolution of PLE spaces in Ulanqab City progressed through three distinct stages:

Stage 1 (2000-2005): During this initial phase, transformations in Ulanqab's PLE spaces were not pronounced. The total amount of production space remained relatively stable, primarily due to agricultural structural adjustments and minor urbanization occupying cultivated land, with the scale of change being limited. The total living space experienced slight growth, but at a low rate, indicating that urbanization in Ulanqab was just commencing, and urban-rural land expansion was slow. The total ecological space remained largely unchanged, with minor fluctuations in localized areas due to natural recovery or slight human disturbance. Overall, in the early 2000s, Ulanqab's development was in its initial stages, and human impact on the land pattern was relatively weak.

Stage 2 (2005-2015): This decade witnessed dramatic changes in production and living spaces. The total production space decreased significantly, with remote sensing imagery indicating a contraction in cultivated land area, potentially exceeding 20%. This was mainly influenced by accelerated urbanization and ecological cropland conversion policies. Conversely, the total living space increased substantially, with a growth rate exceeding 100%, reflecting intensified urban and rural construction activities during this period, particularly the expansion of central urban areas and transportation infrastructure. The total ecological space in this stage showed a trend of first declining then rising; it initially decreased due to development occupation but gradually recovered in the later phase as ecological projects like the Grain for Green Program were implemented, resulting in a slight overall increase. This stage aligned with the national trend of rapid urbanization advancement, presenting a situation of steady progress.

Stage 3 (2015-2020): Constrained by national ecological civilization construction policies and regional sustainable development planning, the conversion trends of living and production spaces in Ulanqab City slowed markedly. The growth rate

Table 1. Classification of rural PLE function coupling degree type.

Coupling Degree (C) Range	Coupling Type	Characterization	Typical Region
0.0~0.3	Low Coupling	Weak interconnection and lack of synergy among PLE functions	Huade County (2000, C=0.28)
0.3~0.5	Antagonistic Coupling	Evident contradictions and poor coordination among PLE functions	Chahar Right Rear Banner (2010, C=0.42)
0.5~0.7	Adaptive Coupling	Preliminary interaction with relatively insufficient coordination among PLE functions	Shangdu County (2010, C=0.63)
0.7~1.0	Coordinated Coupling	Benign interaction and significant synergistic effects among PLE functions	Jining District (2020, C=0.81)

Table 2. Classification of rural PLE function coupling coordination degree types (D value).

Coordination Degree (D) Range	Coordination Type	Characterization	Typical Region	Optimization Suggestions
0.0~0.3	Severe Dislocation Type	Severe imbalance among PLE functions	Chahar Right Middle Banner (2000, D=0.28)	Prioritize ecological restoration, restrict overgrazing, and promote industrial transformation.
0.3~0.5	Mild Dislocation Type	Significant contradictions among PLE functions	Huade County (2020, D=0.51)	Promote water-saving agriculture, enhance compensation for grazing prohibition, and improve infrastructure construction.
0.5~0.6	Near Dislocation Type	Preliminary coordination among PLE functions	Shangdu County (2010, D=0.58)	Develop distinctive local industries and increase the weighting/priority of ecological considerations.
0.6~0.7	Barely Coordinated Type	Initial synergy among functions, but with low efficiency	Siziwang Banner (2020, D=0.72)	Promote green energy (wind power + animal husbandry) and enhance ecological development.
0.7~0.8	Primarily Coordinated Type	Gradual benign interaction among PLE functions	Fengzhen County (2020, D=0.76)	Optimize spatial planning and promote circular agriculture.
0.8~1.0	Intermediate Coordination and Above	High-level synergy among functions, with intensive resource use and balanced development	Jining District (2020, D=0.81)	Strengthen innovation-driven development and deepen the ecological compensation mechanism.

of total living space decreased, with the average annual growth rate falling below 1%, and the rate of production space reduction narrowed. The total ecological space in this stage showed a declining trend, with an average annual decrease of approximately 0.5% to 1%, mainly due to issues like grassland degradation and reduced water resources resulting from the combined effects of climate change and human activities, increasing the pressure on ecological conservation. During this stage, land use regulation in Ulanqab was strengthened, but the task of ecological restoration remained challenging.

In summary, the evolution of PLE spaces in Ulanqab City reflects a process transitioning from slow development to rapid urbanization and then to regulated transition. The future necessitates enhanced protection and restoration of ecological space to promote the coordinated development of PLE spaces.

4 Assessment Results and Discussion of PLE Functions

4.1 Temporal Evolution and Characteristics of PLE Functions

Analysis of PLE function data for Ulanqab City from 2000 to 2020 indicates that its rural revitalization and modernization process demonstrates significant functional synergy alongside regional differentiation. Regarding the production function (see Figure 8), Jining District's value in 2020 increased by approximately 1.8-fold compared to 2000, while Fengzhen City grew by about 1.5-fold, reflecting the notable effectiveness of industrial transformation in the southern region. For the ecological function (see Figure 10), Siziwang Banner consistently remained above the regional average—exceeding it by roughly 40% in 2020—while Zhuozhi County increased by about 25%, indicating steady enhancement of

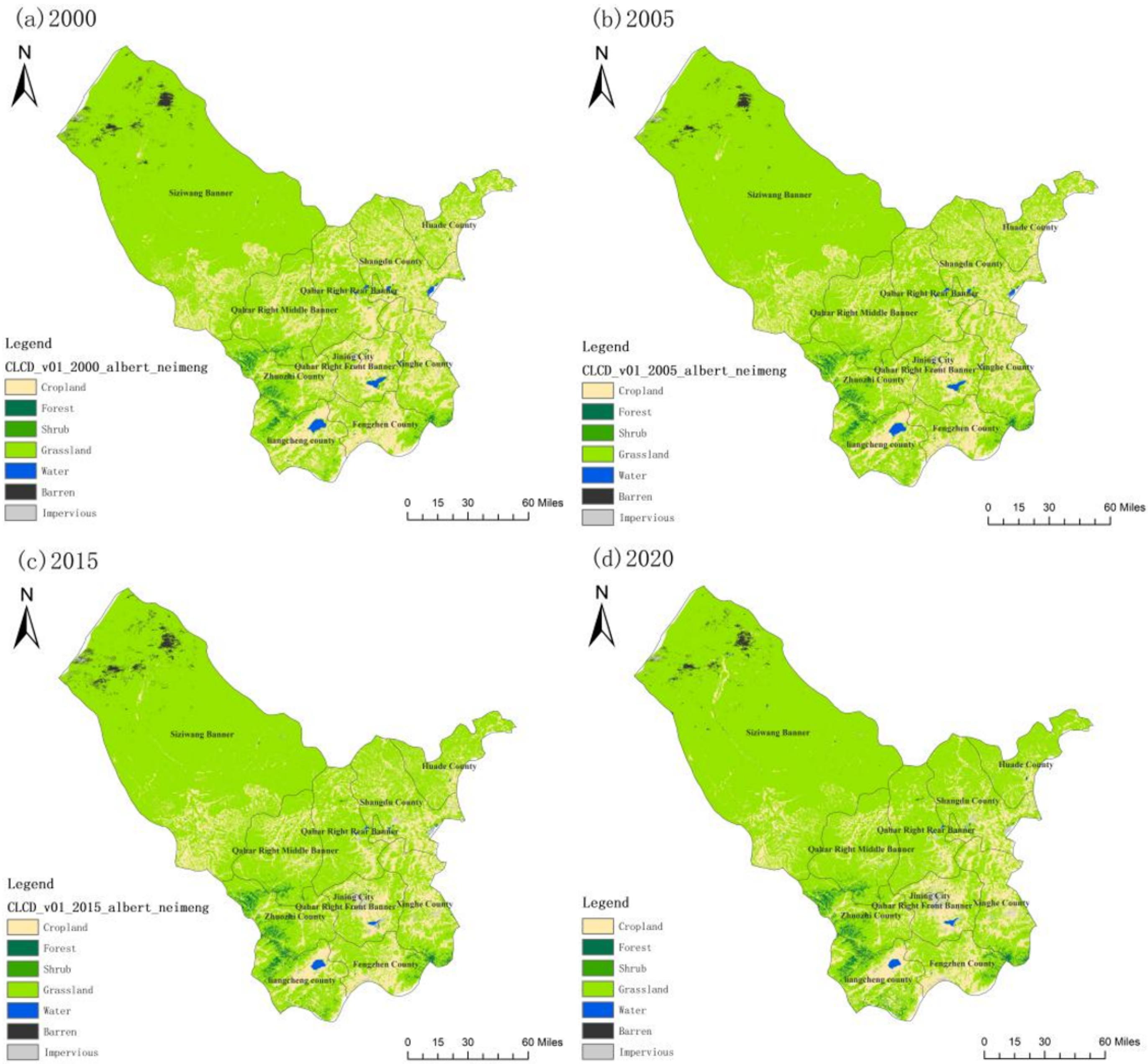

Figure 7. Land-use remote sensing images for four periods (2000–2020) [51].

the northern ecological barrier function. Data on the living function (see Figure 9) show universal improvement across the region. For example, Liangcheng County's 2020 value nearly doubled compared to 2000, and Shangdu County grew by approximately 1.6-fold, demonstrating widespread enhancement in infrastructure and public service levels. However, most function values in Huade County remain below the contemporary regional averages, with its production function reaching only 72% of the mean, highlighting that some northern areas still face developmental lags. These findings suggest that rural revitalization in Ulanqab City should follow differentiated pathways: synergistic upgrading in the south, characteristic cultivation in the central region, and ecological empowerment in the north. Achieving a high-quality modern transformation that integrates PLE functions requires targeted interventions addressing the functional shortcomings revealed by the data.

4.2 Evolution Characteristics of PLE Spatial Structure

From 2000 to 2020, the spatial structure of Production-Living-Ecological (PLE) spaces in Ulanqab City experienced notable changes (see Figure 11): the production space underwent continuous adjustments, the living space steadily

Figure 8. Rural Production Function Values by Banner/County in Ulanqab City.

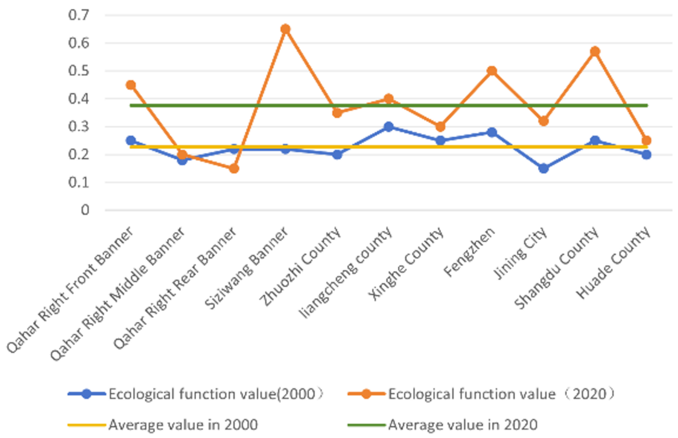

Figure 9. Rural Living Function Values by Banner/County in Ulanqab City.

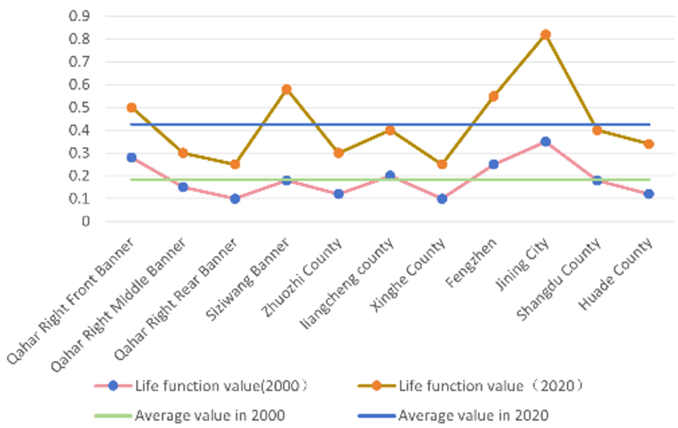

Figure 10. Rural Ecological Function Values by Banner/County in Ulanqab City.

expanded, and the ecological space remained largely stable, though localized areas of degradation and restoration coexisted. Agricultural production space showed a trend of "contraction in the south and stability in the north," while industrial production space agglomerated towards urban peripheries and transportation hubs. Urban living space expanded significantly, and rural living space tended to become more concentrated. Forest ecological space remained generally stable, grassland ecological space exhibited coexisting local degradation and recovery, and water body ecological space was overall stable but showed local shrinkage. Spatially, this manifested a differentiated pattern of "high in the south, low in the north, and transitional in the center."

Examining the evolution characteristics of production space from agricultural and industrial perspectives: The distribution of agricultural production space showed a "southern contraction, northern stability" trend. Traditional agricultural areas in the south, such as Fengzhen, experienced some contraction of agricultural space, potentially related to the Grain for Green program and urbanization occupying farmland. Agricultural space in northern pastoral areas like Siziwang Banner remained relatively stable, reflecting the characteristics of the agro-pastoral ecotone. Industrial production space gradually shifted from scattered distribution towards agglomeration around cities and transportation hubs, forming distinct clusters particularly in southern areas like Jining District and Fengzhen City, indicating the synergistic advancement of industrialization and urbanization.

The evolution characteristics of living space were significant. Urban living space expanded markedly, especially evidenced by the substantial increase in the built-up area of Jining District, demonstrating the polarization effect of the regional central city. Rural living space, while widely distributed overall, tended to concentrate, with some scattered rural settlements likely undergoing consolidation or relocation, aligning with the policy direction of centralized resettlement and optimized layout in rural revitalization.

The evolution characteristics of ecological space were closely linked to policy implementation. Forest ecological space remained generally stable, with possible slight recovery of forest cover in southern hilly and mountainous areas, associated with the implementation of the Grain for Green program and other ecological projects. Grassland ecological space, as the dominant ecological type, was widely distributed but exhibited coexisting local degradation and recovery. Grassland ecological space in northern pastoral areas faced pressure, potentially related to overgrazing and climate change, while recovery was better in some central areas. Water body ecological

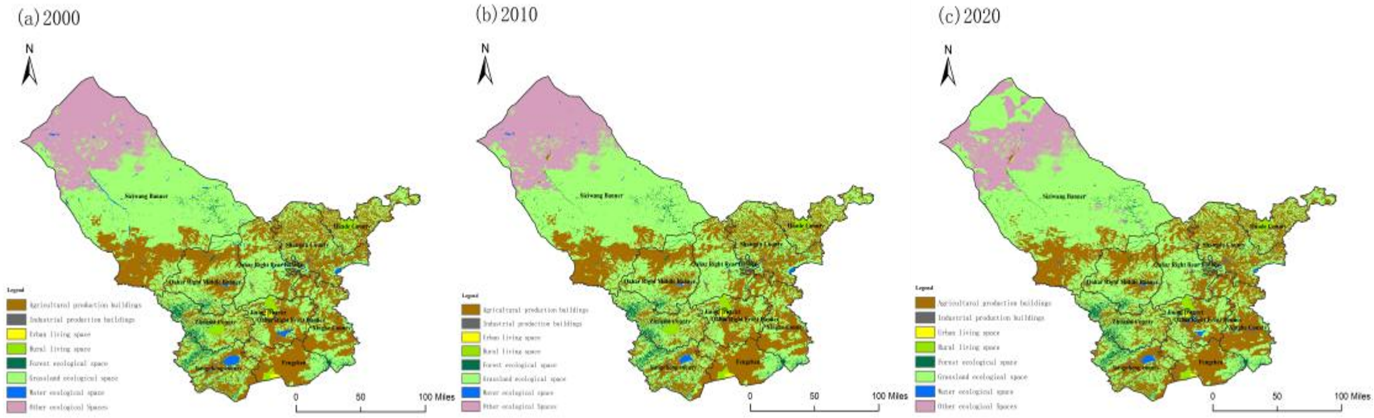

Figure 11. Distribution of PLE Spaces in Ulanqab City, 2000–2020 [52].

space was overall stable but showed local shrinkage, necessitating attention to sustainable water resource utilization.

Overall, the production function in Ulanqab City rose steadily, the living function improved significantly, and the ecological function experienced a fluctuating process of "degradation – slow recovery – gradual improvement." Spatially, it exhibited a differentiated pattern of "high in the south, low in the north, and transitional in the center." Southern areas like Jining District and Fengzhen City had prominent production functions, an increasing share of non-agricultural industries, relatively high living service levels, and their ecological functions showed recovery trends due to earlier policy intervention. Central areas like Chayouzhong Banner and Shangdu County were dominated by agricultural production, with living and ecological functions at medium levels. Northern areas like Siziwang Banner and Huade County had weaker production functions, high reliance on traditional animal husbandry, a fragile ecological baseline, and slow recovery.

4.3 Evaluation of PLE Function Coupling Coordination Degree

The coupling coordination degree (D value) results (see Table 3) show that the coordination types of PLE functions in Ulanqab City have gradually transitioned from severe imbalance to barely coordinated and primarily coordinated, but with significant regional differences. In 2020, Jining District had a D value of 0.81, belonging to the intermediate coordination and above type, indicating a benign interaction among production-living-ecological functions and initial achievements in rural-urban integration and industrial upgrading. Fengzhen City (D=0.76) reached the primarily coordinated type, while Chahar Right Front Banner (D=0.71) was at the barely coordinated level, both reflecting synergistic advances in ecological protection and characteristic agriculture. In contrast, Huade County (D=0.51) remained in a state of near dislocation, and Chahar Right Middle Banner (D=0.49) was in a state of mild dislocation, highlighting persistent issues of ecological constraints and industrial singularity.

4.4 Intelligent Regulation and Optimization Pathways for PLE Functions

In developing intelligent pathways for regulating Production-Living-Ecological (PLE) functions, this study orchestrates a triple transition: from conventional spatial characterization to multi-source remote sensing analytics, from traditional technical management to embedded digital-intelligent governance, and from generalized recommendations to zoned precision strategies. This evolution propels the research toward digitalization, intellectualization, and contextualized implementation.Against the backdrop of deepened integration between agricultural modernization and digital-intelligent technologies, the evolution of PLE functions in Ulanqab City exhibits distinct spatial differentiation and phased characteristics, necessitating a paradigm shift in optimization pathways from traditional spatial regulation to digital-intelligent governance.The southern region should leverage its advantages as a transportation hub and in clean energy to develop an integrated "smart agriculture + digital logistics" model. Future efforts should further strengthen the integrated application of remote sensing monitoring, IoT, and big data to establish a digital supply chain system spanning production, storage, and distribution. This will facilitate the transition of agriculture from scale expansion to quality- and efficiency-driven development.While the northern

Table 3. Evolution of PLE function coupling coordination degree in typical regions of Ulanqab City.

Region	2000	2010	2020	Coordination Type (2020)	Main Characteristics
Jining District	0.42	0.65	0.81	Intermediate Coordination	High level of tertiary industry integration and well-developed public services
Fengzhen City	0.38	0.58	0.76	Primary Coordination	Synergy between specialty agriculture and eco-tourism
Huade County	0.28	0.45	0.51	Mild Dislocation	High ecological pressure and lagging infrastructure
Chahar Right Middle Banner	0.26	0.41	0.49	Near Dislocation	Ecological degradation due to overgrazing

grassland ecological zone faces challenges of pasture degradation and grazing pressure, it simultaneously presents application scenarios for "smart pastoralism." This necessitates the introduction of a grassland ecological remote sensing monitoring platform, intelligent grazing systems, and complementary wind-solar-livestock energy models to achieve precise management of animal husbandry within ecological constraints.As an agro-pastoral ecotone, the central region should develop smart forestry and precision eco-agriculture based on remote sensing and sensor networks while maintaining the cropland-forest land balance. This approach will enhance the digital capabilities of understory economy and specialized cultivation practices.

Furthermore, existing research predominantly remains at the level of proposing optimization suggestions for isolated components. Even when zonal strategies are put forward, they often exist in parallel without being integrated through an intelligent central platform capable of aggregating multi-source data, simulating complex system interactions, and supporting holistic decision-making across the entire region.This study addresses this gap by constructing an integrated sky-air-ground digital monitoring platform and an intelligent decision support system [42]. To tackle challenges such as regional agricultural non-point source pollution and urban expansion encroaching on farmland, the platform utilizes multi-source data—including satellite remote sensing, UAV aerial surveys, and ground IoT sensors—to achieve comprehensive spatiotemporal monitoring of soil, water quality, meteorology, crop growth, and land use changes. Space-based, air-based, and ground-based data are uniformly uploaded to the cloud, where a big data platform performs standardization processes such as data cleaning, forming a highly efficient and intelligent "Integrated Sky-Air-Ground Environmental Information Sensing Network."Simultaneously, the platform incorporates AI-driven decision models that dynamically assess fertilizer application rates, soil moisture status, and ecological redlines based on real-time remote sensing monitoring data. This provides a precise foundation for the coordinated governance of Production-Living-Ecological (PLE) spaces.

Only by deeply embedding digital-intelligent technologies into the entire process of regional spatial function regulation can Ulanqab City achieve high-quality development that balances agricultural modernization and ecological security.

4.5 Challenges and Opportunities for Rural Revitalization and Modernization

The southern region achieves functional synergy through industrial diversification and ecological restoration, providing a demonstration for urban-rural integration and modernization; the central region needs to further balance agricultural production and ecological protection, expanding understory economy and circular agriculture models; the northern region, with its fragile ecological baseline and strong traditional industry characteristics, is the challenging area for PLE coordination and modern transformation. The competition between production and ecological spaces intensifies during the urbanization process, with construction land expansion in suburban areas encroaching on high-quality farmland and ecological land, constraining sustainable rural development. Additionally, agricultural non-point source pollution (relatively high fertilizer and pesticide intensity) is a major obstacle to improving ecological function. However, national policies such as the Beijing-Tianjin Sandstorm Source Control and the construction of renewable energy demonstration bases provide new momentum for regional PLE functional synergy. This can be combined with digital intelligence, industrial upgrading, and smart agriculture to promote sustainable rural development.

5 Conclusions and Recommendations

5.1 Main Conclusions

From 2000 to 2020, the structure of PLE spaces in Ulanqab City underwent significant changes, generally characterized by: continuous adjustment of the production space structure, continuous expansion of living space, and basic stability of the overall ecological space pattern alongside localized degradation and restoration. Analyzing the internal driving forces of this evolution urgently requires the introduction of a digital-intelligence perspective. The intensification of the production function and expansion of living space in the southern region are closely related to the transformation from traditional agriculture to intensification and smart agriculture,foreshadowing the necessity of building a smart agriculture big data platform to integrate production and circulation information. The balanced situation of the rise and fall of agricultural and forestry spaces in the central region provides a typical scenario for applying remote sensing and IoT technologies to achieve precise eco-agriculture management. The fluctuations of the ecological function in the northern grassland area highlight the urgent need to establish a digital twin system for the grassland ecosystem, enabling real-time monitoring and intelligent regulation of grazing activities and vegetation restoration. Therefore, the evolution of the spatial pattern is not only a reflection of historical processes but also the spatial framework for future construction of an integrated sky-air-ground intelligent monitoring and decision-making system.

5.2 Policy Recommendations

To achieve the goals of synergistic PLE space development and agricultural modernization in Ulanqab City, the following differentiated strategies and policy recommendations are proposed:

1. Southern Region: Deep Integration of Smart Agriculture and Digital Supply Chains. Focusing on Jining and Fengzhen, move beyond the simple overlay of "production + logistics" and prioritize the construction of a regional smart agriculture big data platform. Integrate high-resolution remote sensing monitoring of crop growth, IoT sensor collection of soil moisture and meteorological data, and market circulation information to build an end-to-end digital supply chain system from the "production end" to the "consumption end." Through data empowerment, achieve precise fertilization and irrigation, optimize storage and logistics layout, and accurately match market demand, ultimately promoting the transition of agriculture towards high quality and high value-added, consolidating its leading role as a demonstration zone for urban-rural integration.

2. Central Region: Smart Eco-Agriculture Based on Remote Sensing and IoT. In the agro-pastoral ecotone areas like Chayouzhong Banner and Shangdu County, promote an integrated sky-air-ground intelligent monitoring network for eco-agriculture. Use multi-temporal remote sensing imagery to dynamically monitor spatial changes in the cropland-forest ecotone, combined with IoT devices deployed in fields to perceive soil moisture, nutrient status, and pest information in real-time. Establish precise management models for the understory economy, providing optimal solutions for characteristic planting and ecological breeding, achieving a refined balance between agricultural production and ecological conservation (e.g., maintaining Grain for Green achievements), and enhancing the value of ecological products.

3. Northern Region: Intelligent Animal Husbandry and Digital Supervision of Grassland Ecology. Targeting ecologically fragile areas like Siziwang Banner and Huade County, the core is to build an intelligent animal husbandry system. This could involve fitting livestock with Beidou positioning collars, using UAVs for patrol grazing to monitor NDVI and soil moisture, combined with satellite remote sensing to assess grassland carrying capacity. Through big data analysis, provide herders with intelligent early warnings for grass-livestock balance and optimized grazing suggestions, and connect with "wind-solar-livestock complementary" smart energy systems to achieve quality and efficiency improvement and sustainable development of animal husbandry under the premise of protecting grassland ecology.

4. Overall Coordination: Construct an Agricultural Big Data Decision Support System [44]. To address cross-regional challenges such as agricultural non-point source pollution and urban encroachment on farmland, there is an urgent need to build a Ulanqab-wide "PLE Space" Agricultural Big Data Decision

Support Platform. This platform should integrate multi-source data including geographic information, remote sensing monitoring, environmental statistics, and socio-economic data, with built-in AI-driven scenario simulation and optimization models. It should be capable of dynamically simulating the responses of PLE functions under different policy scenarios (e.g., ecological compensation standards, industrial access conditions), providing scientific and intelligent decision support for territorial spatial planning, environmental regulation, and industrial layout, thereby achieving a governance upgrade from local optimization to overall coordination.

5.3 Research Outlook

This study, based on multi-source remote sensing and statistical data, constructed a digital-intelligent assessment framework for PLE functions oriented towards agricultural modernization, preliminarily revealed the spatiotemporal evolution patterns and coupling coordination mechanisms of PLE spaces in Ulanqab City from 2000 to 2020, and proposed differentiated intelligent regulation pathways. However, PLE space optimization is a complex giant system evolution process that is multi-scale and dynamic. Future research can be further deepened in the following aspects:

Firstly, regarding data dimensions and sensing depth, current limitations primarily relying on macro-level remote sensing monitoring and statistical data can be overcome by actively introducing social sensing data, such as mobile terminal signaling and social media data, along with high-frequency monitoring data from ground-based Internet of Things (IoT) networks. This will enable the precise capture of socio-economic activities, population movements, and micro-environmental changes. Particularly in the agricultural sector, integrating UAV-based hyperspectral remote sensing with in-field sensor networks to construct an integrated sky-air-ground precision sensing system for the entire crop growth cycle will provide unprecedented data support for analyzing the micro-level mechanisms through which agricultural production influences Production-Living-Ecological (PLE) spaces.

Secondly, regarding assessment models and intelligent algorithms, efforts should be made to upgrade from static "pattern–process" description to dynamic "simulation–prediction." Future research can introduce cutting-edge algorithms such as multi-agent simulation [45] and machine learning to construct PLE space evolution models. For example, simulating farmers' production decisions and their spatial effects under different policy scenarios through Agent-Based Modeling (ABM), or using machine learning to mine the key driver factor thresholds for PLE functional synergy and conflict, thereby achieving multi-scenario intelligent simulation and early warning of agricultural modernization paths and their ecological impacts, providing forward-looking previews for decision-making.

Finally, regarding application orientation and interdisciplinary integration, future research should pay more attention to the entity construction and operationalization of smart decision support systems. Concretize the zonal intelligent pathways proposed in this study into operable digital tools, developing dedicated digital twin platforms for specific regions such as the southern smart agriculture zone and the northern intelligent animal husbandry zone, integrating data, models, and knowledge to provide one-stop services including real-time monitoring, assessment, simulation, and optimization suggestions for government departments and operating entities. Simultaneously, strengthen the deep integration of multiple disciplines such as human geography, information science, agronomy, and ecology, exploring the adoption process, impact mechanisms, and optimization strategies of embedding digital-intelligent technologies into the rural territorial system from a multidisciplinary comprehensive perspective, ultimately promoting the substantive transformation of research results from "theoretical innovation" to "governance practice," providing replicable, scalable intelligent solutions for high-quality agricultural development and rural revitalization in the northern agro-pastoral ecotone and other similar regions.

Data Availability Statement

The data used in this study are publicly available from the following sources:

(1) Administrative division data from the National Geomatics Center of China (https://cloudcenter.tianditu.gov.cn/administrativeDivision);

(2) Supporting datasets available on Figshare (https://doi.org/10.6084/m9.figshare.26028769);

(3) Socioeconomic and auxiliary data from Harvard

Dataverse (https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/GIYGJU);

(4) MODIS vegetation index data (MOD13A2, Collection 6) accessed via Google Earth Engine (https://developers.google.com/earth-engine/datasets/catalog/MODIS_006_MOD13A2).

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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