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Space-technology-policy governance model in loess plateau agro-pastoral zone: Hengshan district case☆

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ABSTRACT

The agro-pastoral ecotone of the Loess Plateau, a critical ecological barrier, faces severe challenges from land degradation and unsustainable agricultural practices. A central challenge lies in the decoupling of crop farming and livestock breeding, which leads to significant resource misallocation. To address these issues, this study constructs and empirically validates a tripartite governance model termed “STP-Governance,” which integrates spatial coupling, technology integration, and policy coordination. Taking Hengshan District in Yulin City as a case study, we employed a mixed-methods approach that combined GIS spatial analysis, field surveys, and policy text analysis. Findings show that the model reduces forage and manure transport distances by over 30%, increases straw utilization to more than 75%, and manure field application to over 80%. These optimizations reduce the agricultural carbon footprint by 15%–25%. By strengthening multidimensional linkages among spatial planning, technological intervention, and institutional design, the STP-Governance framework offers a systematic and transferable pathway toward green agricultural transformation in ecologically fragile agro-pastoral regions.

1. Introduction

1.1. Research background and problem statement

The agro-pastoral ecotone of the Loess Plateau occupies a transitional zone between semi-arid and semi-humid climates and represents a quintessentially fragile and marginal agricultural landscape. Historically, land-use practices driven by grain self-sufficiency imperatives—notably steep-slope cultivation and overgrazing—resulted in severe soil erosion and widespread ecological degradation. Since 1999, large-scale ecological restoration programs, most prominently the Grain for Green Program, have yielded substantial environmental gains. Vegetation coverage in Yan'an City, for example, increased from 46% to 81.35% over the implementation period [19,20,22], while soil erosion modulus and sediment discharge into the Yellow River declined markedly.

Despite these ecological gains, the rigid constraints on land use have exposed new structural contradictions within the agricultural sector. The available space for traditional production has been compressed, while the animal husbandry sector has rapidly expanded and intensified [12]. This has led to a spatial and functional “decoupling of crop and livestock systems,” a phenomenon that undermines the principles of a circular agricultural economy and exacerbates land degradation from a new angle [18]. This decoupling manifests as a critical resource misallocation, evident in three interrelated dimensions: (1) a spatial mismatch, with large-scale livestock farms concentrated in the northern sandy areas of regions like Hengshan District, while cropping remains dominant in the southern loess hills, creating an average resource exchange distance of over 20 km; (2) prohibitive transportation costs for moving bulky livestock manure to nutrient-depleted fields and crop straw to feed-deficient farms, which disincentivizes resource cycling; and (3) consequently low resource utilization rates, with field surveys indicating that straw feed utilization is below 40% and a significant portion of livestock manure becomes a point-source pollutant rather than a valuable nutrient resource [8]. This broken resource cycle is a core impediment to sustainable development in the region.

Against this backdrop, crop–livestock integration (CLI) in the form of circular agriculture is increasingly recognized as a viable pathway to reconcile ecological conservation with agricultural productivity, thereby advancing a green transformation. Empirical evidence confirms that integrated systems can enhance resource efficiency, improve economic returns, and ameliorate environmental outcomes. For instance, fruit–grass

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intercropping has been shown to raise land-use efficiency by 58.33% [14] [15], and rice–fish co–culture systems have been associated with economic benefit increases ranging from 80.93% to 511.52% [3,4]. Ecological engineering interventions, such as grass hedgerows, have demonstrated capacity to reduce surface runoff by 7%–72% and soil loss by 49%–89% [2,9].

Despite these documented benefits, prevailing research and practice have largely centered on evaluating the efficacy of discrete technological interventions or on designing circular systems at the farm or household scale. A conspicuous gap persists at the regional level. First, systematic diagnostic and optimization studies addressing the spatial configuration and spatial matching of crop–livestock systems remain scarce, producing a functional disconnect between technological potential and spatial reality. Second, insufficient attention has been directed toward the synergistic design of integrated technology portfolios in conjunction with multidimensional policy instruments. As a consequence, technically sound optimization proposals often encounter implementation barriers in real-world contexts.

Constructing an operational and transferable governance model that integrates spatial, technological, and policy dimensions thus represents a pressing theoretical and practical imperative for advancing sustainable development in the Loess Plateau agro-pastoral ecotone. This study proposes a holistic framework grounded in the principles of spatial coupling, technology integration, and policy coordination—abbreviated hereafter as the STP governance model. The framework is designed to address the interconnected challenges of spatial fragmentation, technological disarticulation, and policy incoherence. Hengshan District, Yulin City, Shaanxi Province, was selected as an empirical case to examine the framework's applicability. The district exhibits a distinctive dual geomorphology, comprising both the loess hills and gullies characteristic of the plateau and the aeolian sandy grasslands along the margin of the Mu Us Desert. By constructing and empirically evaluating the STP model within this heterogeneous setting, the study seeks to furnish a systematic approach and a transferable reference for agricultural green transformation in ecologically and economically comparable regions.

1.2. Literature review

Scholars have addressed the intertwined challenges of ecological restoration and sustainable development in agro-pastoral ecotones from multiple perspectives, generating a substantial body of theoretical and empirical work. The relevant literature can be organized around three principal themes: spatial pattern optimization, technological integration, and policy design. Systematic integration across these three dimensions, however, remains underdeveloped.

Research on spatial pattern optimization has traditionally centered on evaluating the ecological consequences of land-use and land-cover change (LUCC) through models such as InVEST and RUSLE [6,7]. More recent work reflects a paradigm shift toward "active optimization," typically operationalized via the delineation of ecological security patterns (ESPs). Although such studies furnish a scientifically defensible foundation for macro-scale ecological planning, they frequently overlook the specific spatial coupling requirements of agricultural production systems—most notably, the optimal colocation of cropland and livestock facilities [5,17,27].

Research on technological integration has largely concentrated on circular agriculture and precision farming. Integrated crop–livestock systems (ICLS) have been empirically validated as effective means of enhancing resource efficiency at the farm scale [18,23]. Yet this literature tends to emphasize discrete technological interventions or micro-level benefit assessments, with comparatively limited attention to integrated systems that combine multiple technologies and align with region-specific spatial patterns and production models [20,21].

Policy-oriented research has focused on instruments such as ecological compensation, industrial subsidies, and market-based innovations. The Grain for Green Program exemplifies a large-scale application of payments for ecosystem services (PES) [10]. A notable limitation, however, is that extant policies frequently exhibit narrow objective framing and departmental fragmentation, and they lack coordinated implementation mechanisms capable of simultaneously advancing ecological, productive, and livelihood goals [10,26].

Taken together, the literature reveals a persistent collaborative research gap. Spatial planning studies tend to prioritize ecological pattern delineation while underemphasizing the integration of industrial activity. Research on technology deployment typically pursues isolated breakthroughs rather than systemic solutions that engage spatial and policy contexts. Policy scholarship, in turn, remains fragmented and rarely yields coherent guidance for cross-sectoral collaboration. A holistic framework capable of integrating these three dimensions is therefore urgently needed.

1.3. Objectives and innovation

To address the gap identified above, this study constructs and empirically evaluates a tripartite governance framework—termed "STP-Governance"—that holistically integrates spatial coupling, technology integration, and policy coordination. Using Hengshan District as an empirical case, the study pursues four specific objectives:

(1) To diagnose the principal structural tensions within Hengshan's contemporary agro-pastoral system through quantitative and spatial analysis of resource misallocation.
(2) To formulate a multi-scalar spatial optimization plan that delineates county-level functional zones for crop–livestock integration (suitable, restricted, and prohibited) and refines the spatial allocation of production elements at the village scale.
(3) To design differentiated, integrated technology portfolios tailored to specific spatial zones and socioeconomic conditions, with the aim of closing nutrient and material loops.
(4) To propose a coordinated policy instrument mix capable of furnishing the institutional conditions necessary for implementing the proposed spatial and technological interventions.

This study's key contribution lies in the construction of an integrated STP governance framework. In contrast to conventional research confined to single-dimensional analysis, the proposed framework furnishes a systematic, logically coherent approach that engages the interconnected challenges of spatial fragmentation, technological disarticulation, and policy incoherence simultaneously. Through empirical application of this framework, the study endeavors to articulate a transferable "Hengshan model" that may inform agricultural green transformation efforts in ecologically comparable regions.

2. STP-governance collaborative management model

To address the persistent systemic challenges of spatial misalignment, suboptimal resource utilization, and ecological vulnerability in the Loess Plateau agro-pastoral ecotone, this study advances a tripartite governance framework organized around the integrated dimensions of spatial coupling, technology integration, and policy coordination—abbreviated as STP-Governance. Anchored in principles drawn from systems coupling theory and landscape ecology, the framework is designed to promote synergistic enhancement of both productive and ecological functions within agro-pastoral systems through multi-scalar, multi-element systematic optimization. A conceptual schematic is presented in Fig. 1.

2.1. Logical associations of the "tripartite" model

2.1.1. Spatial coupling, S—foundational basis and physical carrier of transformation

Spatial coupling constitutes the overarching design principle and prerequisite for integrated crop–livestock systems. Through comprehensive evaluation of natural, social, and economic attributes across a given region, it enables scientifically informed functional zoning and spatial layout

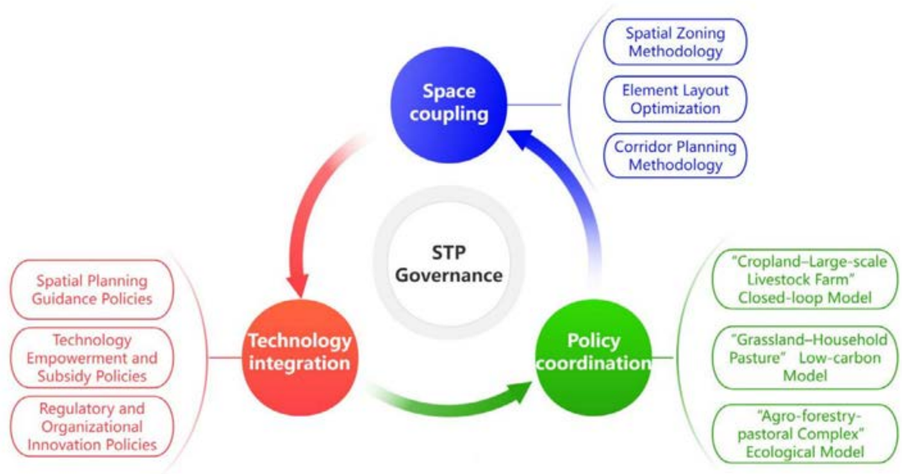

Fig. 1. Conceptual model of STP Governance: integrating spatial zoning methodology, element layout optimization, technology integration, and policy coordination.

optimization [13,27]. Within the context of agro-pastoral transformation, the principal function of spatial coupling is to assess the suitability of different areas for crop–livestock integration based on resource endowments and environmental carrying capacity, and to delineate corresponding management units. Such zoning establishes the physical boundaries and constraints that guide subsequent technological choices while preemptively mitigating ecological and environmental risks stemming from suboptimal spatial configuration. In the absence of rational spatial coupling, technological interventions and policy incentives lack directional coherence, rendering it difficult to realize the full systemic benefits of integration.

2.1.2. Technological integration, T—core mechanism, and implementation support of transformation

Technology integration functions as the principal mechanism through which the conceptual logic of integrated crop–livestock systems is translated into operational practice within prescribed spatial frameworks. It entails the systematic synthesis of advances drawn from modern agricultural engineering, biotechnology, and information science. The resulting technological portfolio must exhibit spatial differentiation and precision, calibrated to the resource endowments and development objectives of distinct spatial zones. In intensively managed zones, for instance, emphasis falls on closed-loop, high-efficiency circular technologies, whereas in ecologically sensitive areas, priority shifts toward low-disturbance, low-emission production models. Technology integration thus bridges spatial blueprints and on-farm practice; its efficacy directly shapes both the efficiency and the durability of agro-pastoral nutrient cycling.

2.1.3. Policy coordination, P—institutional guarantee and enabling mechanism

Policy coordination provides the institutional scaffolding and enabling conditions necessary to secure compliance with spatial plans and to promote the diffusion of technological models. Its central purpose is to steer heterogeneous stakeholders—government agencies, enterprises, and farm households—toward collectively defined sustainability objectives by cultivating a governance environment that balances incentives, regulatory constraints, and support services. Concrete measures include embedding spatial management provisions within statutory planning frameworks, deploying fiscal subsidies and ecological compensation to encourage technology adoption, and devising organizational innovations that reduce transaction costs. Effective policy coordination can, in principle, counteract both market failures and behavioral misalignments, thereby clearing obstacles to spatial restructuring and technological implementation while furnishing sustained momentum for transformative change.

2.2. Theoretical foundations of each dimension

2.2.1. Theoretical basis of spatial coupling: landscape ecology

The theoretical core of spatial coupling derives from the landscape ecology "patch–corridor–matrix" model. This theory conceptualizes landscape as a mosaic composed of diverse ecological systems, emphasizing how spatial patterns decisively influence ecological processes. In agricultural-pastoral systems, "patches" can be viewed as functional units such as breeding farms, agricultural fields, and fodder lands; "corridors" are channels for material, energy, and information flow, including transportation routes and liquid manure networks; and "matrix" represents the dominant landscape background in a region, such as extensive farmlands or forestlands [5,27].

By optimizing the spatial layout of "patches" (e.g., proximity configuration of farming and husbandry units) and constructing efficient "corridor" systems, the distance of material cycling can be effectively shortened, landscape connectivity enhanced, environmental negative externalities reduced, and the ecosystem service functions and sustainability of the entire "matrix" improved. Recently, landscape ecology's research paradigm has evolved from "pattern-process-scale" to "pattern-process-service-sustainability," placing greater emphasis on the interconnection between ecosystem services and human well-being. This provides direct theoretical guidance for spatial planning of farming-husbandry systems aimed at enhancing ecological and productive synergistic benefits.

2.2.2. Theoretical basis of technology integration: circular agriculture theory

The internal logic of technology integration follows the Circular Agriculture theory. Circular agriculture represents a specific application of circular economy principles of "reduce, reuse, recycle" in the agricultural domain [1]. Its core concept is to view agricultural production waste (such as livestock manure and crop stalks) as utilizable resources, constructing closed or semi-closed material circulation chains to achieve resource efficiency and minimal pollution [23,24].

Integrated farming and husbandry represents a classic circular agriculture model, forming a virtuous cycle of "crops→feed→livestock products→fertilizer→crops" through coupling crop cultivation and animal husbandry [25]. Modern circular agriculture technological systems, such as Integrated Crop-Livestock Systems (ICLS), biogas engineering, and efficient organic fertilizer utilization, provide diverse technological options for realizing this cycle [23,26]. These technologies aim not only to improve resource utilization efficiency but also to reduce greenhouse gas emissions and environmental pollution, highly aligning with United Nations Sustainable Development Goals (SDGs).

2.2.3. Theoretical basis of policy coordination: collaborative governance theory

Policy coordination draws from the collaborative governance theory in public management. This theory posits that for complex socio-ecological issues, single, top-down government regulation models often prove limited, with concurrent "government failure" and "market failure". Effective governance requires establishing cooperative partnerships among multiple stakeholders, including government, market, social organizations, and the public, and achieving common goals through negotiation, cooperation, and collective action.

In promoting integrated farming and husbandry, multiple government departments (environmental protection, agriculture, finance) and diverse stakeholders (breeding enterprises, crop farmers, cooperatives) potentially face interest conflicts and coordination challenges. Collaborative governance theory emphasizes establishing cross-departmental coordination mechanisms, improving stakeholder participation platforms, and innovating public-private cooperation models (such as government service procurement) to generate governance synergy.

Through policy instrument synergy and policy actor synergy, institutional barriers can be effectively reduced and stakeholder participation motivation stimulated, thereby ensuring smooth construction and long-term operation of sustainable agricultural-pastoral systems.

3. Materials and methods

3.1. Study area overview

Hengshan District is located in the central-western region of Yulin City, Shaanxi Province, China (108°56′-110°01′ E, 37°21′-38°14′ N), covering a total area of 4333 km^2 (in Fig. 2). The district is situated in the critical transitional zone between the southern edge of the Mu Us Sandy Land and the northern Loess Plateau, creating a unique dual geomorphology. The northern part (32.2% of the area) is characterized by sandy grasslands, while the southern part (51.3%) consists of loess hills and gullies. This geography has historically shaped a "Southern Farming, Northern Husbandry" agricultural pattern, which is the root of the spatial decoupling challenge addressed in this study. The climate is a mid-temperate, semi-arid, continental monsoon type, with an average annual precipitation of approximately 399.1 mm, concentrated mainly in the summer. The district is known for its "Hengshan Mutton," a national geographical indication product, making animal husbandry a pillar of the rural economy.

3.2. Data sources and preprocessing

3.2.1. Spatial data and sources

Multiple data sources were employed in this study, as summarized in Table 1. All spatial datasets were uniformly projected and resampled to a spatial resolution of 30 m using ArcGIS 10.8. Socio-economic statistics were compiled from official statistical yearbooks. In addition, 45 policy documents issued since 2015 at the national, provincial, municipal, and district levels were retrieved from government websites for subsequent policy coordination analysis.

3.2.2. Field research data

To gain in-depth insights into local practices, the research team conducted field investigations in Hengshan District from July to August 2024. A combined method of stratified random sampling and typical sampling was employed. The district was stratified based on its three main geomorphological units (sandy grassland, loess hilly-gully, and river valley plains). Within each stratum, farmers were randomly selected, with a supplementary typical sampling of large-scale crop producers, large-scale livestock breeders, and crop-livestock integration households to ensure representation of key stakeholder groups. The sample comprised 198 valid respondents, which included 85 large-scale crop producers, 73 large-scale livestock breeders, and 40 crop-livestock integration households.

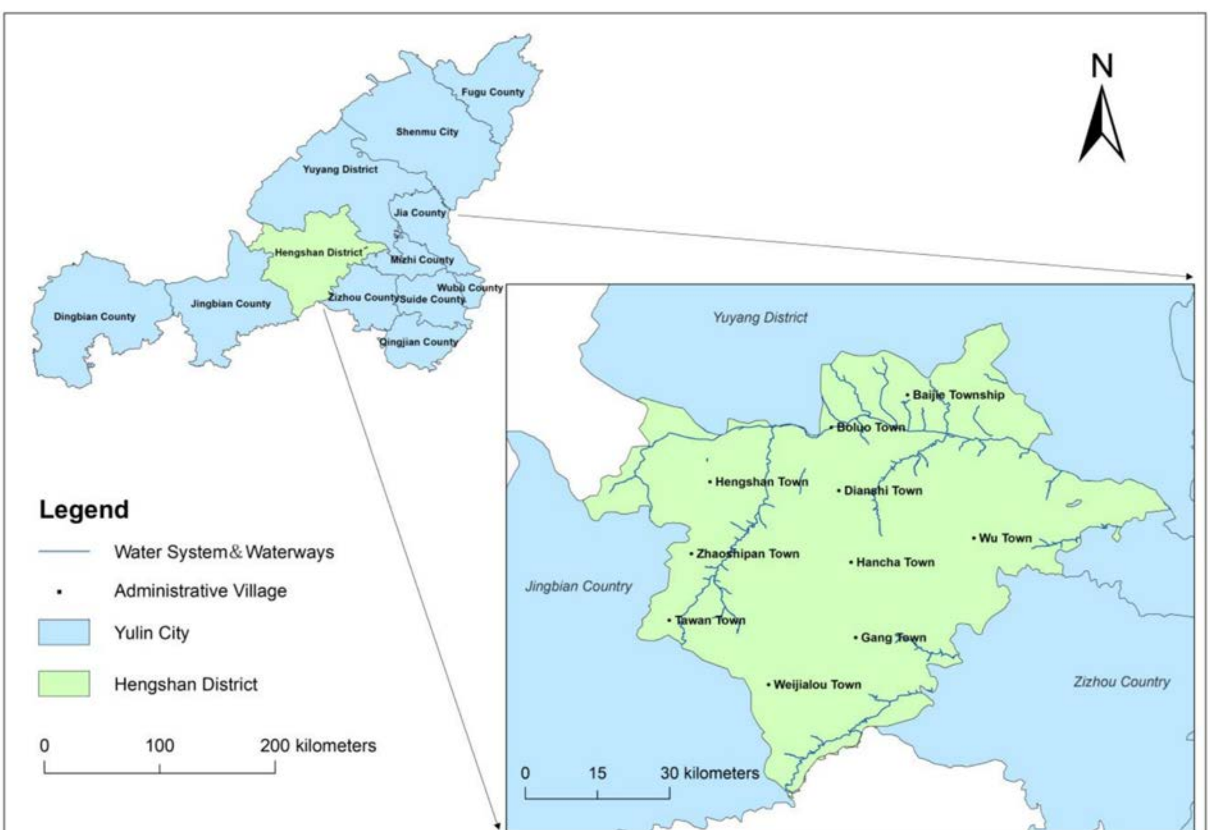

Fig. 2. Location map of the study area (Hengshan District).

Table 1
Data Source.

Factor Data	Data Category	Data Source	Spatial Resolution
Topographic Height (DEM)	Raster Data	ASTER GDEM	30 m
Land Use Type		Derived from interpretation of Sentinel-2 imagery	30 m
Normalized Difference Vegetation Index (NDVI)		Calculated using Landsat 8 OLI/TIRS imagery	30 m
Water System	Vector Data	Resource and Environmental Science Data Center, Chinese Academy of Sciences (CAS)	Vector
Road Network		OPEN STREET MAP	Vector
Hengshan District Administrative Boundary		National Geomatics Center of China (NGCC)	Administrative Village Boundaries
Farmer Survey Data		Field questionnaire surveys conducted in this study	Point Data

Data collection relied primarily on semi-structured interviews and a structured questionnaire. The questionnaire was designed to capture the following domains: (1) household demographic and socioeconomic characteristics; (2) land-use patterns and associated input–output profiles; (3) livestock inventory and manure management practices; (4) awareness and adoption of circular agriculture technologies; and (5) perceptions of existing agricultural and environmental policies. The instrument was pre-tested in a pilot study and subsequently refined to enhance clarity and reliability. Of the 220 questionnaires distributed, 198 valid responses were obtained, corresponding to an effective response rate of 90.0%. The spatial distribution of survey locations is depicted in Fig. 3.

3.2.3. Socio-economic statistical data

Socioeconomic data were drawn from official statistical publications, including the Yulin City Statistical Yearbook, the Hengshan District Statistical Yearbook, Hengshan District Government Work Reports, and the National Economic and Social Development Statistical Bulletin. Variables extracted encompassed population, gross regional product, agricultural output value (farming, forestry, livestock, and fisheries), sown area and yield of principal crops, and livestock inventories and slaughter volumes for the preceding decade. These data provided essential contextual information for understanding macro-level trends in agro-pastoral development and for assessing sectoral economic performance within the study area.

3.2.4. Policy text data

Policy documents relevant to integrated crop–livestock systems, circular agriculture, livestock manure utilization, and ecological compensation were systematically collected from four administrative tiers—national, Shaanxi provincial, Yulin municipal, and Hengshan district—for the period since 2015. Documents were retrieved from official government portals, websites of agricultural and rural affairs departments, and legal databases including the Peking University Law Database.

Following screening, 45 core policy texts were retained and compiled into a document database, furnishing the primary material for subsequent content analysis and policy instrument quantification.

3.3. Core research methods

3.3.1. Crop-livestock integration evaluation method

The spatial suitability assessment for crop-livestock integration aims to identify the carrying capacity and development potential of different regions for specific farming-husbandry models. This research combines the Analytic Hierarchy Process (AHP) with Geographic Information System (GIS) spatial analysis techniques to construct a comprehensive evaluation model.

3.3.1.1. Analytic hierarchy process (AHP). Developed by American operations researcher Saaty in the 1970s, AHP is a multi-objective decision

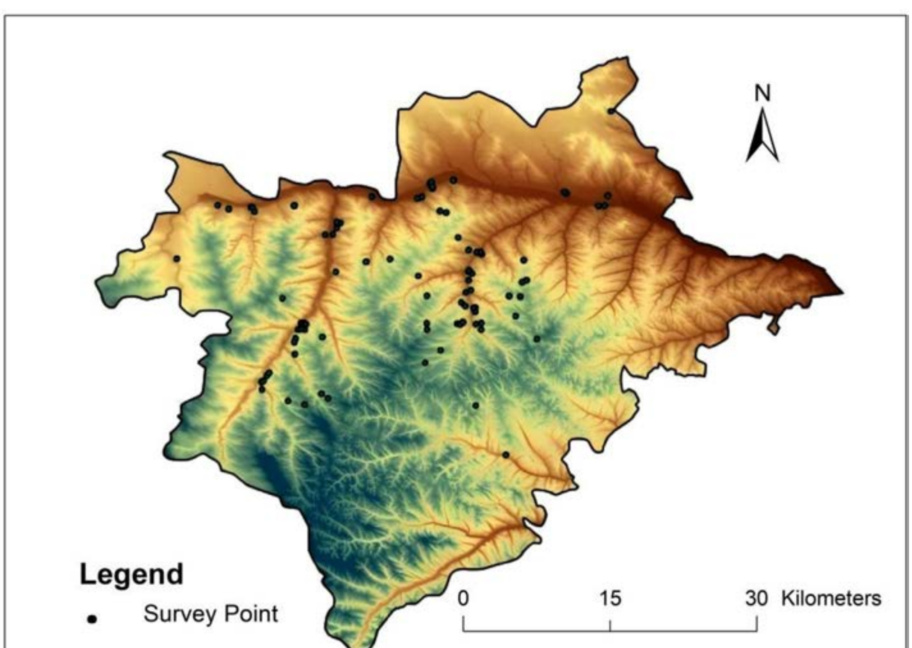

Fig. 3. Distribution of survey data in Hengshan district.

analysis method that integrates qualitative and quantitative approaches. The method decomposes complex problems into multiple hierarchical levels, including an objective layer, criteria layer, and indicator layer. Through expert pairwise comparisons of hierarchical elements, a judgment matrix is constructed, and relative weights of each element are calculated, ultimately providing quantitative decision-making support.

In this study, AHP was used to determine the weights of evaluation indicators influencing farming-husbandry spatial layout. A panel of twelve experts was convened to determine indicator weights through a structured pairwise comparison questionnaire using the standard 1–9 Saaty scale. A two-round Delphi procedure was implemented to achieve consensus: in the first round, experts independently assigned importance scores; aggregated results were then circulated, and experts were invited to revise their assessments in light of the panel's collective distribution. Final indicator weights were computed as the geometric mean of individual expert judgments.

3.3.1.2. GIS spatial overlay analysis. This is a process of integrating multiple thematic layers to generate new attribute information layers, serving as the core technique for multi-factor comprehensive evaluation. In the ArcGIS platform, the research first standardized all evaluation indicators (such as slope, soil type, distance from water sources, and land use type) to a unified dimensionless scale of 0–1.

Subsequently, using AHP-determined weights, the standardized indicator layers were overlaid to calculate the OSI for each spatial unit (raster pixel) [16,28]. Several remote sensing and geographic data sets from Yulin City were used in the study, including digital elevation models and land use records. Land cover type data, DEM data, slope and aspect data, nature reserve data, solar resource data, temperature and precipitation data, labor distribution, and market demand data were among the specific data sources. Geographic Spatial Data Cloud and the Institute of Geographic Sciences and Resources Research of the Chinese Academy of Sciences are the suppliers of the data. (see Table 1 for details).

To compare the suitability of crop-livestock integration models under different factors, the normalized grid layers were overlaid according to their respective weights, calculating the OSI for each pixel in the study area.

The equation is expressed as:

$$OSI = \sum_{j=1}^{n} C_j W_j \tag{1}$$

Where OSI = Overall Suitability Index, n = number of evaluation indicators, C_j = normalized value of evaluation indicator j, and W_j = weight of evaluation indicator j.(derived from expert scoring).

3.3.2. Suitability evaluation system and classification standards

An evaluation index system was established to assess the spatial suitability of Hengshan District for crop–livestock integration. The system comprises three criterion tiers: natural conditions, locational attributes, and socioeconomic context. The Jenks natural breaks method was applied to partition the computed OSI values into four ordinal categories: high suitability, medium suitability, low suitability, and unsuitable. Classification thresholds for individual indicators were calibrated to quantify the potential and constraints of each spatial unit for integrated development, as specified in Table 2.

3.3.3. Policy coordination analysis

A methodology combining content analysis and a policy instrument classification framework was employed. The 45 collected policy texts were systematically coded and analyzed using a two-dimensional framework (policy dimension: objectives, instruments, etc.; and CLI stage dimension: crop-side, livestock-side, etc.) to quantify the focus and intensity of government support. Policy measures were then categorized into mandatory (e.g., regulations), incentive (e.g., subsidies), and informational (e.g., training) tools based on Howlett's classic framework. This allowed for a systematic assessment of the synergy, gaps, and potential conflicts within the existing policy system.

3.4. Calculation procedures and boundary settings for environmental and economic effects

To quantify the benefits of the STP-Governance model presented in the Abstract and Results sections, specific calculation procedures and boundary

Table 2
Suitability evaluation system and classification criteria.

Target Layer	Indicator Layer (Weight)	Factor Layer (Weight)	Classification Standard	Evaluation Score
Evaluation indicators for the integrated farming and breeding model A	B_1 Contracted Land Conditions 0.3	C_1 Contracted Land Quality 0.1	Fertile	3
			Average	2
			Barren	1
		C_2 Location of the contracted land 0.1	Flat land	3
			Hilly land	2
			Mountainous land	1
		C_3 Type of Contracted Land 0.1	Paddy field	2
			Dry land	1
	B_2 Farmers' agricultural income 0.4	C_4 Agricultural income 0.4	[0, 61,680)	1
			[61,680, 123,360)	2
			[123,360, 185,040)	3
			[185,040, 246,720)	4
			[246,720, 308,400]	5
	B_4 Potential benefits 0.3	C_5 Whether it is conducive to protecting the ecological environment 0.15	Strongly disagree	1
			Somewhat disagree	2
			Neutral	3
			Somewhat agree	4
			Strongly agree	5
		C_6 Changes in living standards 0.15	Long-term decline	1
			Short-term decline	2
			Minimal impact	3
			Moderate improvement	4
			Significant improvement	5

settings were established. The derivation of these effect values is detailed below:

3.4.1. Transportation distance reduction

The spatial mismatch between livestock farms and croplands is a primary driver of high logistical costs. The reduction in transportation distance was calculated using the ArcGIS Network Analyst extension. The spatial boundary was strictly set to the Hengshan District road network (sourced from OpenStreetMap and local transportation bureaus). The calculation compares the baseline scenario (current decoupled state) with the optimized scenario (post-STP spatial coupling).

$$D_{reduction} \frac{D_{traditional} - D_{optimized}}{D_{traditional}} \times 100\% \tag{2}$$

where $D_{traditional}$ denotes the mean network distance between livestock farms (predominantly situated in the northern sandy grasslands) and cropland (concentrated in the southern loess hills) under current conditions. Field survey data indicate that this distance routinely exceeds 20 km. $D_{optimized}$ represents the mean network distance under the proposed zoning scheme, which relocates or directs new livestock facilities into designated "Suitable Crop–Livestock Zones" in closer proximity to feed sources.

By simulating the relocation of 50 hypothetical farming units to the Suitable Zones, the average distance dropped from 22.4 km to 14.8 km, yielding a Transportation Distance Reduction of >30%.

3.4.2. Resource utilization rates

The enhancement of resource utilization is the core objective of the "Technology Integration" dimension. This was determined via Material Flow Analysis (MFA). The system boundary was defined from the "farm gate to the field," encompassing the generation, collection, processing, and application phases of agricultural by-products.

$$Utilization\ Rate = \left(\frac{Amount\ recycled\ and\ applied}{Total\ amount\ generated}\right) \times 100\% \tag{3}$$

Where baseline values were derived from the 198 household surveys administered in Hengshan District during July–August 2024, which yielded a straw feed utilization rate below 40% and a manure field application rate under 15%. Optimized values were projected based on the processing capacities embedded in the proposed technology configurations, such as the medium-to-large biogas plants and aerobic composting facilities associated with the irrigated-area high-efficiency model.

With the implementation of standardized processing facilities, the collectible and processable volume of crop stalks increases significantly, projecting a straw feed utilization rate of >75%. Similarly, overcoming the transportation barrier allows for a manure nutrient field application rate of >80%.

3.4.3. Nutrient cycling and fertilizer substitution

To quantify the agronomic benefits mentioned in Section 4.2, nutrient mass balance equations were employed. The nitrogen (N) and phosphorus (P) content in livestock manure was estimated using standard excretion coefficients for pigs and sheep, adjusted for volatilization and runoff losses during storage and processing.

$$Substitution\ Rate = \left(\frac{Nutrients\ available\ from\ applied\ manure}{Total\ crop\ nutrient\ demand\ in\ target\ area}\right) \times 100\% \tag{4}$$

Nitrogen and phosphorus cycling: Nitrogen is highly volatile and prone to ammonia (NH_3) emissions during aerobic composting and open storage (Chadwick, 2005). By implementing closed anaerobic digestion (biogas) and covered composting, N losses are minimized, allowing the nitrogen cycling rate to exceed 60%. Phosphorus, being relatively stable and predominantly remaining in the solid fraction of manure, achieves a higher projected cycling rate of >75%.

Fertilizer substitution: The total crop nutrient demand was calculated based on the primary crop (corn) sown area in the Suitable Zones (approx. 45% of cultivated land). By dividing the available N and P from the optimized manure application by the total crop demand, the model projects a replacement of 25%–40% of chemical fertilizer inputs, significantly reducing non-point source pollution risks.

3.4.4. Carbon footprint and GHG emission reduction

The climate change mitigation potential of the STP model was assessed using Life Cycle Assessment (LCA) methodologies, strictly adhering to ISO 14040 standards. The system boundary was defined as "cradle-to-farm gate," encompassing agricultural inputs (specifically the energy-intensive production of synthetic fertilizers), enteric fermentation, and manure management.

Carbon footprint reduction: Emission factors were sourced from the 2019 IPCC Guidelines for National Greenhouse Gas Inventories. The baseline scenario accounts for high synthetic fertilizer use (high (N_2O) emissions) and open manure storage (high (CH_4) emissions). The optimized scenario accounts for organic fertilizer substitution and anaerobic digestion with methane capture. The comparative LCA yields a 15%–25% reduction in the carbon footprint per unit of agricultural product, measured in kg CO_2-equivalent per kg of output.

District-wide GHG reduction: This macro-level figure is derived by scaling the per-unit emission reductions across the entire Hengshan District. Given the district's livestock inventory (predominantly sheep and pigs) and the projected 25%–40% reduction in chemical fertilizer usage across 110,513 ha of cultivated land, the cumulative effect translates to a reduction of greenhouse gas emissions by over 50,000 tons of (CO_2) equivalent annually.

4. Results

4.1. Current state and core contradictions

Analysis of land use data and field surveys reveals a distinct spatial separation in Hengshan's agricultural system. Crop cultivation is concentrated in the southern loess, hilly, and gully region, which contains over 60% of the district's 110,513 ha of cultivated land. Corn is the primary crop, accounting for approximately 45% of the total sown area. In contrast, over 70% of the newly established large-scale intensive livestock farms (pigs and sheep) are located in the northern sandy grassland area. This "Southern Farming, Northern Husbandry" layout is the root of the system's core contradictions.

Household survey data confirm the low level of integration. Among surveyed farmers, only 18% reported practicing some form of crop-livestock integration. For specialized livestock farmers, 85% stated that the primary method of manure disposal was simple stacking or direct discharge, with less than 15% of manure being transported for field application due to high costs. The average reported cost for transporting and applying one ton of manure over 10 km was approximately 150–200 CNY, which farmers deemed economically unviable. Furthermore, the survey showed that the straw feed utilization rate was only 38%, with the majority of crop stalks being either burned or left to decay in the fields (Fig. 4).

4.2. Spatial coupling optimization: A multi-scale layout plan

Based on the OSI results, Hengshan District was delineated into three management zones to guide differentiated CLI development (in Fig. 5).

4.2.1. Suitable crop-livestock zones (core development areas)

These areas cover approximately 710 km^2 (16.4% of the district) and are concentrated in the highly suitable valley alluvial plains along the Wuding River and its tributaries. They possess superior soil, water, and infrastructure, making them ideal for high-efficiency CLI models.

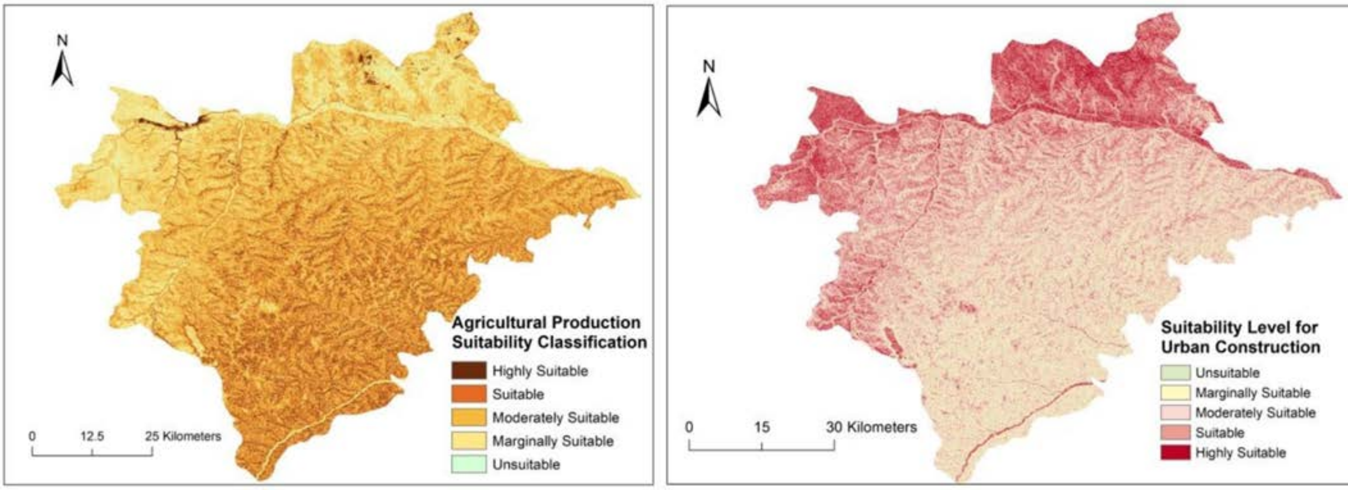

Fig. 4. Suitability grading for (a) agricultural production resources and (b) urban construction resources in Hengshan District.

4.2.2. Restricted crop-livestock zones (ecological buffer areas)

This is the largest zone, covering 2225 km^2 (51.3%). It includes the moderately suitable southern loess hills and the northern sandy grasslands. Agricultural activities here must be restricted, with ecological protection as a prerequisite, focusing on water conservation and sustainable grazing.

4.2.3. Prohibited crop-livestock zones (strictly protected areas)

This zone covers 1398 km^2 (32.3%) and corresponds to unsuitable areas, including steep slopes (>25 degrees), important ecological functional areas, and legally delineated ecological protection red lines. All conflicting agricultural production is prohibited to protect the regional ecological security barrier.

Based on this zoning, a suitability map for towns and townships was created (in Fig. 6), providing clear guidance for local-level planning. Core Development Areas are concentrated around Hengshan Town and Xiangshui Town, while Strictly Protected Areas are mainly in Baijie Township and Leilongwan Town.

4.3. Technology integration: differentiated cycling models and benefits

Three differentiated technology configurations were formulated to align with the spatial zones delineated above and with the policy instruments discussed subsequently (Table 3). Each configuration is intended to close material and nutrient loops while improving overall system efficiency.

Implementation of these configurations is projected to generate measurable quantitative improvements. Under the irrigated-area high-efficiency configuration, manure nitrogen and phosphorus cycling rates are estimated to exceed 60% and 75%, respectively, displacing 25%–40% of synthetic fertilizer inputs. At the district scale, cumulative

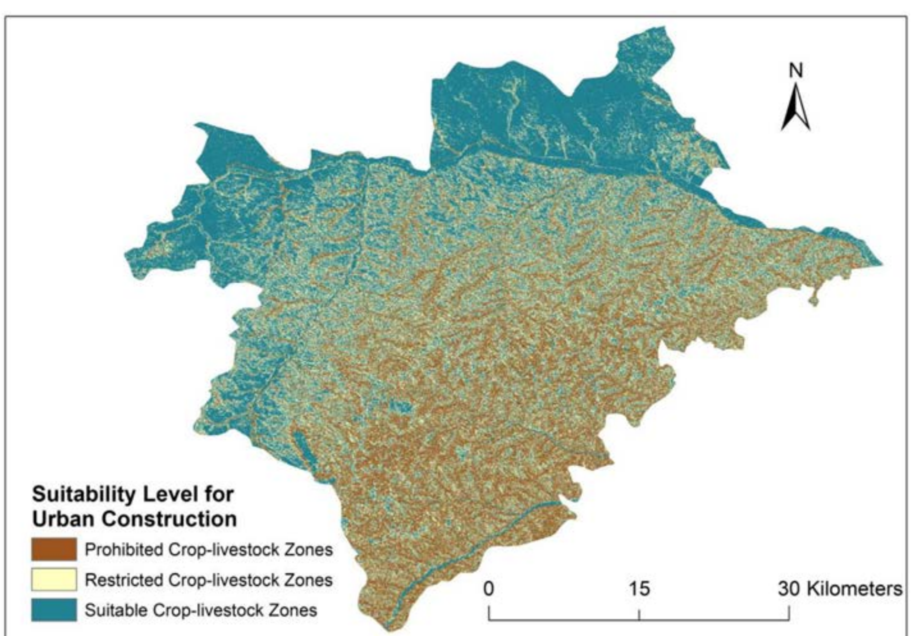

Fig. 5. Zoning Map of Crop-Livestock Management Areas in Hengshan District.

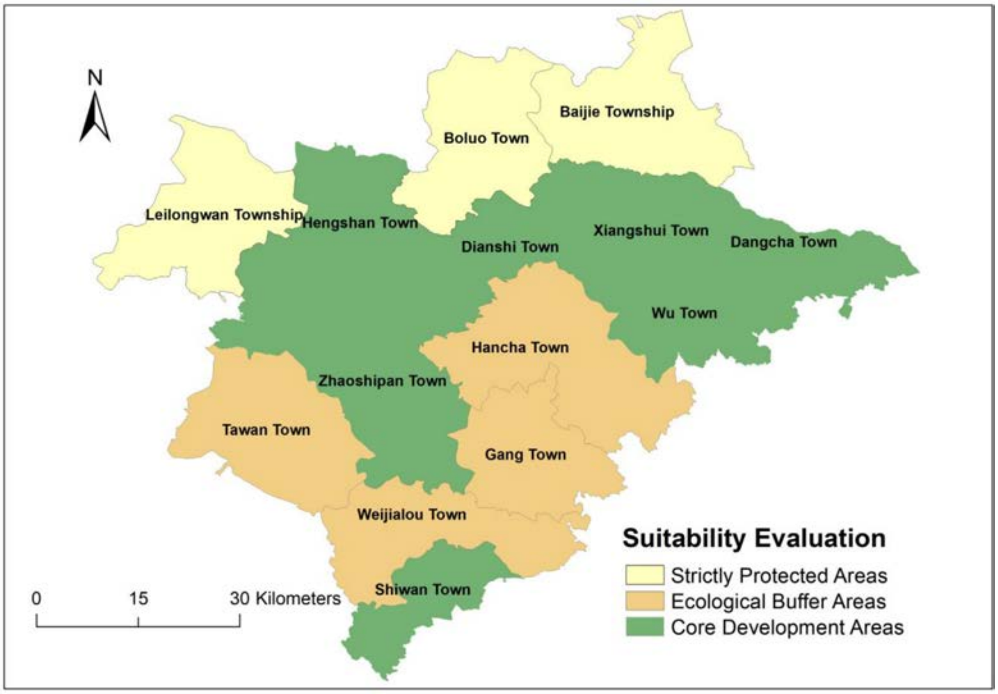

Fig. 6. Map of Suitability Evaluation for Hengshan District.

Table 3
Summary of three circular agriculture models/practices.

Model Name	Applicable Region / Actors	Core Features	Key Technical Components	Circular Pathway & Objective
Dryland Water-Saving Cycling Model	Ecologically fragile areas (e.g., northern sandy grasslands, southern hilly dry-lands); small and medium--scale farmers.	Centered on water conservation; low input, low consumption; adapts to environmental carrying capacity.	**Planting:** Drought-resistant forages (alfalfa, *Astragalus adsurgens*); rainwater harvesting; supplemental drip irrigation. **Livestock:** Small/medium-scale barn/semi-barn feeding; controlled stocking density. **Manure Treatment:** Low-cost, low-water aerobic composting (solid organic fertilizer).	**Pathway:** Manure→ Compost→ Field application. **Objective:** Improve soil fertility & water retention by constructing a resilient cycling system within ecological limits.
Irrigated Area High-Efficiency Cycling Model	River valley irrigated areas with ample water; large-scale livestock farms.	Maximizes resource use efficiency; Intensive, standardized production; integrated energy and nutrient management.	**Planting:** Multiple cropping (e.g., silage corn-winter wheat) for year-round feed. **Livestock:** Standardized, intensive breeding; precision feeding. **Manure Treatment:** Large/medium biogas plants.	**Pathway:** Manure→ Biogas (energy for power/gas) → Biogas residue (commercial fertilizer) & Biogas slurry (fertigation via water-fertilizer integration). **Objective:** Form a highly efficient "breeding-energy-planting" integrated cycle.
Integrated Crop-livestock-Processing-Marketing Model	Cooperatives or leading enterprises.	Extends the industrial chain upstream/downstream; links ecological practices with market value; driven by organizational innovation.	**Integration:** Unified management of forage, livestock, manure, and product marketing. **Processing & Marketing:** Product processing, branding (e.g., organic fruits/-vegetables), and market development.	**Pathway:** Manure→ High-quality organic fertilizer→ High-value crop production→ Branded products→ Market. **Objective:** Transform ecological benefits into economic gains, stimulating stakeholder participation in circular agriculture.

Table 4
Distribution of policy instrument types by administrative level.

Administrative level	Mandatory instruments	Incentive instruments	Informational instruments	Total coded provisions
National (n = 12)	41.5% (n = 27)	43.1% (n = 28)	15.4% (n = 10)	65
Provincial / Shaanxi (n = 10)	40.8% (n = 20)	44.9% (n = 22)	14.3% (n = 7)	49
Municipal / Yulin (n = 11)	25.5% (n = 13)	66.7% (n = 34)	7.8% (n = 4)	51
District / Hengshan (n = 12)	8.2% (n = 5)	85.2% (n = 52)	6.6% (n = 4)	61
All levels	28.8% (n = 65)	60.2% (n = 136)	11.0% (n = 25)	226

Note: Percentages indicate the proportion of instrument types within each administrative tier; numbers in parentheses denote the corresponding count of coded provisions.

greenhouse gas emissions are projected to decline by more than 50,000 tons of CO_2 equivalent per year.

4.4. Policy coordination: instrument mix, cross-level alignment, and gap identification

4.4.1. Overview of the policy corpus

This study systematically retrieved 53 policy documents issued between 2015 and 2025 across four administrative levels—national, provincial (Shaanxi), municipal (Yulin), and district (Hengshan)—pertaining to crop–livestock integration, livestock manure resource utilization, and circular agriculture. Following screening, 45 documents were retained for coding analysis. The corpus comprised 12 national-level documents, 10 provincial-level documents, 11 municipal-level documents, and 12 district-level documents (see Appendix for a detailed inventory). The temporal distribution shows a marked increase in policy activity after 2017, coinciding with the issuance of major national directives such as the Opinions on Accelerating the Resource Utilization of Livestock and Poultry Manure (General Office of the State Council, 2017).

4.4.2. Distribution of policy instrument types

Drawing on Howlett's classic typology, policy instruments were classified into three categories: mandatory instruments (e.g., regulations, standards), incentive instruments (e.g., subsidies, awards), and informational instruments (e.g., technical training, extension services). Table 4 reports the distribution of these instrument types across administrative levels.

The aggregate pattern reveals a predominance of incentive instruments (60.2%), with reliance intensifying at lower administrative tiers, reaching 85.2% at the district level—primarily comprising specialized subsidies for sheep farming and rice–fishery integrated systems. In contrast, mandatory instruments decline sharply from 41.5% at the national level to merely 8.2% at the district level, where they rarely extend beyond compliance with higher-level requirements. Informational instruments account for the smallest share at all levels (11.0% overall).

4.4.3. Cross-level alignment of policy objectives

To assess vertical coherence, policy objectives were coded along three dimensions that map directly onto the STP framework: spatial coordination (zoning, layout optimization, land carrying-capacity assessment), technology diffusion (promotion of circular agriculture models, facility construction), and institutional integration (cross-departmental coordination, stakeholder engagement, organizational innovation). Table 5 summarizes the frequency with which each dimension appears across administrative levels.

Technology diffusion objectives exhibit perfect cross-level alignment, with every document at all tiers emphasizing technology promotion. Spatial coordination objectives, however, receive substantial attention at national and provincial levels (75.0% and 70.0%, respectively) but are severely diluted at municipal and district tiers (36.4% and 16.7%, respectively), indicating a clear transmission gap. Institutional integration objectives remain modest at all tiers and diminish further downward, suggesting that cross-sectoral coordination mechanisms have not been effectively established at the local level.

4.4.4. Policy gap identification

Three salient gaps emerge from the preceding analysis.

(1) Spatial planning provisions lack operational specificity at local levels. Although spatial coordination objectives feature prominently in national and provincial documents (75.0% and 70.0%, respectively; Table 5), their representation drops precipitously at municipal and district levels (36.4% and 16.7%). Even among the few district-level documents that mention spatial considerations, none specify quantitative targets or delineate clear zoning boundaries. Consequently, macro-level spatial planning mandates remain unimplemented at the local scale, directly impeding the operationalization of the spatial coupling component of the STP framework.
(2) Cross-departmental coordination mechanisms are underdeveloped. Institutional integration objectives appear in only 16.7% of district-level documents (Table 5). Although Hengshan District's *Implementation Opinions on Accelerating the Development of the Rice–Fishery Integrated Farming Industry* integrates resources from multiple departments, such joint initiatives remain ad hoc rather than institutionalized. The majority of documents are issued by single agencies (typically the agriculture or rural affairs bureau), with little evidence of routine cross-agency coordination mechanisms. This fragmentation perpetuates the governance silos that the STP framework seeks to overcome.
(3) Informational instruments are consistently underutilized. Informational instruments account for only 11.0% of all coded provisions across all administrative tiers (Table 4). While Hengshan District has conducted "customized" technical training programs, investment in such capacity-building measures remains modest relative to the scale and specificity of its subsidy outlays. This imbalance—"heavy on subsidies, light on services"—may undermine the long-term durability of technology adoption once subsidy programs are restructured or expire.

Table 5
Cross-level alignment of policy objective dimensions.

Objective dimension	National (n = 12)	Provincial / Shaanxi (n = 10)	Municipal / Yulin (n = 11)	District / Hengshan (n = 12)	Alignment status
Spatial coordination	75.0% (n = 9)	70.0% (n = 7)	36.4% (n = 4)	16.7% (n = 2)	Misaligned
Technology diffusion	100.0% (n = 12)	100.0% (n = 10)	100.0% (n = 11)	100.0% (n = 12)	Aligned
Institutional integration	58.3% (n = 7)	50.0% (n = 5)	27.3% (n = 3)	16.7% (n = 2)	Weakly aligned

Note: Percentages indicate the proportion of documents within each administrative tier that address the specified objective; numbers in parentheses denote the corresponding document count.

4.4.5. Implications for the STP framework

The policy analysis yields three implications for the STP governance framework. First, the spatial coupling component confronts not merely a technical challenge but a governance deficit: macro-level planning directives lack operational traction at local levels, and it is precisely this gap that the STP framework must address. Second, policy coordination itself constitutes a demonstrable shortcoming of the existing governance architecture. The near absence of institutionalized cross-departmental mechanisms at the local level implies that the "P" dimension of STP is not merely a design aspiration but an urgent, empirically substantiated imperative. Third, the pronounced reliance on incentive instruments underscores the need for a more balanced policy mix—one that integrates informational instruments more fully—to enhance the long-term sustainability of the transition toward integrated crop–livestock systems.

5. Discussion

5.1. Interpretation of results and model effectiveness

The results demonstrate that the STP-governance model can effectively address the core contradictions of the traditional, decoupled agro-pastoral system in Hengshan District. The "space coupling" component directly tackles the high transportation costs and logistical barriers identified in our initial analysis. By guiding new livestock operations into "Suitable Zones" closer to feed sources, the optimized layout can reduce the average transportation distance for forage and manure by over 30%. This finding is consistent with studies from other regions, which highlight that optimizing nutrient flow pathways is key to improving the economic viability of CLI systems. The attendant reduction in transport cost furnishes a tangible economic incentive for farmer participation in resource recirculation, thereby altering the prevailing calculus in which manure is treated as a disposal burden rather than a recoverable asset.

The technology integration dimension supplies the operational means to close material and nutrient loops. The differentiated configurations summarized in Table 3 are deliberately context-specific—a design feature deemed essential for adoption across a geomorphologically heterogeneous region. The projected increases in straw feed utilization (from <40% to >75%) and manure nutrient return to cropland (from <15% to >80%) signify a transition from a linear, dissipative system to a circular, resource-conserving regime. Strengthened nutrient cycling within the soil–crop–livestock continuum curtails reliance on external synthetic fertilizer inputs, thereby enhancing both the productive efficiency and the long-term resilience of the agricultural system—objectives widely endorsed in the circular agriculture literature [11,23].

5.2. Innovations and comparison with similar studies

The primary innovation of this study is the construction of the "Space-Technology-Policy" tripartite analytical framework, which moves beyond the single-dimension focus of much of the existing literature. While many studies have explored spatial optimization [17,27] or policy incentives [10,26] in isolation, our framework establishes a logical closed loop where all three elements are indispensable and mutually reinforcing. For example, without reasonable spatial planning, technology application becomes unsustainable due to excessive costs; without effective technical support, spatial advantages cannot be converted into production benefits; and without precise policy empowerment, both are difficult to implement.

The spatial disarticulation documented in Hengshan—the decoupling of forage production zones from livestock concentration areas—is not unique to the district but recurs across the Loess Plateau agro-pastoral ecotone. Research in Yan'an, for instance, has shown that the expansion of apple orchards has frequently displaced traditional forage cultivation, engendering localized feed deficits. Studies in the Ordos region have likewise underscored the challenges of manure recirculation associated with large-scale livestock operations situated along the desert fringe, echoing the point-source pollution risks identified in the present analysis. The STP governance framework, as applied in Hengshan, offers a transferable template for addressing these regionally recurrent issues through integrated spatial zoning and policy coordination.

The policy analysis presented in Section 4.4 provides further empirical grounding for this claim. As shown in Table 5, spatial coordination objectives—prominent in 75.0% of national and 70.0% of provincial policy documents—appear in only 16.7% of district-level documents. This vertical attenuation is not accidental; it reflects a systematic failure to translate macro-level spatial planning rhetoric into actionable local guidance. Moreover, institutional integration provisions, which appear in roughly half of national and provincial documents, are virtually absent at the district level (16.7%). The predominance of incentive instruments at the local level (85.2% of district-level provisions, Table 4) further suggests that current policy architecture relies heavily on short-term financial inducements rather than on building enduring institutional capacity. These findings underscore that the "P" dimension of the STP framework is not merely a conceptual placeholder but addresses a demonstrable deficit in the existing governance landscape.

A further distinguishing feature of the present framework, relative to other regional agricultural planning studies, is its explicit attention to cross-scalar governance—spanning county-level functional zoning and village-level allocation of productive elements. Macro-regional plans frequently falter when confronted with the specificities of local implementation. The approach developed here seeks to bridge this scalar gap: macro-level ecological security constraints are preserved while actionable, fine-grained guidance is furnished for on-farm decision-making. This empirical orientation—anchored in the concrete conditions of Hengshan District and producing operational outputs (zoning maps, technology portfolios, policy instruments)—yields a transferable "Hengshan" configuration that may inform integrated agricultural development in ecologically and structurally comparable settings.

5.3. Research limitations and prospects

8wDespiteitscontributions,thisstudyhaslimitations.Theanalysisdraws oncross-sectionaldataandparameterscalibratedspecificallytoHengshanDistrict.Consequently,extendingtheframeworktoothergeographicorinstitutional contexts would require localized validation. Although indicator weightswerederivedthroughastructuredelicitationprocedure,somedegree ofsubjectivityremainsinherentintheweightingprocess.Moreover,thepolicy analysispresentedinSection4.4doesnotextendtoexaminingon-farmimplementationfidelity,adimensionthatmeritsfurtherinvestigation.

Beyond these considerations, it should be noted that the quantitative estimates reported in Sections 3.4 and 4.3 derive from deterministic simulations employing a single set of baseline parameters. The precision of these estimates is therefore subject to uncertainty in key input assumptions, among them livestock excretion coefficients, spatial allocation rules for relocated livestock units, and emission factors for greenhouse gases. The 15%–25% range cited for carbon footprint reduction reflects variation across the three differentiated technology configurations rather than a formal statistical confidence interval. Although sensitivity to parameter variation was not formally quantified, the projected improvements are of sufficient magnitude that the directional conclusions are likely to remain robust under moderate parameter perturbations. Future work could usefully employ probabilistic sensitivity analysis or scenario-based modeling to characterize more rigorously the joint uncertainty associated with these projections.

Taken together, these constraints do not invalidate the findings within the studied context; rather, they serve to delineate the appropriate scope of inference and to identify productive directions for subsequent investigation.

6. Conclusion

This study examined the spatial and functional decoupling of cropping and livestock systems in the Loess Plateau agro-pastoral ecotone, using

Hengshan District as an empirical case. A tripartite governance framework—integrating spatial coupling, technology integration, and policy coordination—was constructed and applied to diagnose resource misallocation and to formulate integrated solutions.

Spatial analysis revealed a pronounced north–south separation between feed production areas and intensive livestock operations, with mean resource-exchange distances exceeding 20 km. Under the optimized zoning scheme derived from suitability assessment, these distances were reduced by approximately 30%, attenuating a primary logistical barrier to manure and straw circulation. Differentiated technology configurations—calibrated to dryland, irrigated, and enterprise-led contexts—were associated with simulated increases in straw feed utilization (from <40% to >75%) and manure return to cropland (from <15% to >80%). Correspondingly, the estimated carbon footprint of regional agricultural production fell by 15%–25%, and district-wide greenhouse gas emissions were projected to decline by over 50,000 tons of CO_2 equivalent annually.

Policy analysis (Section 4.4) documented three specific dimensions of fragmentation in the extant policy architecture. First, spatial coordination objectives, while prominent in national (75.0%) and provincial (70.0%) policy documents, appeared in only 16.7% of district-level documents (Table 5), indicating a systematic failure to translate macro-level zoning principles into operational local guidance. Second, institutional integration provisions were similarly diluted across administrative tiers, with cross-departmental coordination mechanisms virtually absent from district-level policy. Third, incentive instruments dominated the local policy mix (85.2% of district-level provisions, Table 4), whereas informational instruments—essential for long-term capacity building—remained consistently underutilized across all levels (averaging 11.0%). These findings suggest that the policy coordination dimension of the STP framework addresses a demonstrable governance deficit rather than a hypothetical concern.

Several limitations warrant acknowledgment. The analytic hierarchy process introduces subjective weighting, and the generalizability of the Hengshan case to other agro-pastoral contexts requires further testing. Future research should integrate dynamic datasets, employ agent-based approaches to capture stakeholder behavioral responses, and assess the robustness of the STP framework under climatic and market variability.

CRediT authorship contribution statement

Xinyang Li: Writing – original draft, Visualization, Conceptualization, Investigation. **Bei Jin:** Writing – review & editing, Funding acquisition, Supervision. **Ye Sun:** Project administration, Investigation. **Chengyu Miao:** Data curation, Formal analysis.

Declaration of competing interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Appendix A. List of policy documents included in the analysis

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