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Research on the Synergistic Model of Pasture and Photovoltaic Complementarity and Ecological Restoration Technology in the Cold Highland Pastoral Areas of the Qinghai-Xizang Plateau

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Abstract: Driven by the goal of ' double carbon ', the large-scale wind power photovoltaic base in Shagehuang accelerates the layout. The alpine pastoral area of the Qinghai-Xizang Plateau bears the triple pressure of clean energy development, grassland ecological restoration and animal husbandry efficiency. However, the alpine region is ecologically fragile, the recovery period is long, and the grass-livestock balance constraints are strong. The existing results are scattered and out of line with engineering needs. This paper systematically reviews the system mechanism, application mode, key technology, ecological zoning evaluation and engineering practice progress of photovoltaic-pastoral complementary. The results showed that array shading, precipitation redistribution and wind field weakened the inter-plate-under-plate-edge microhabitat, and the vegetation-soil response was non-linearly differentiated along the drought gradient. The heat island effect was significant in the extremely arid area and the ecological positive feedback in the semi-arid area. The four models of natural grassland light grazing, artificial pasture mixed sowing, ecological restoration gradual and compound industry integration have their own applicable boundaries; array adaptation, grass species configuration, grazing control and water and fertilizer regulation constitute the key technical system. The two-dimensional zoning method based on ecological sensitivity and construction suitability tends to be mature, and the local-regional-global multi-scale effect framework is initially established. Aiming at the problem of disconnection between static results and engineering requirements, it is proposed to establish a long-term positioning monitoring network, clarify the multi-factor coupling threshold, develop a mechanism-data hybrid evaluation method, and formulate lightweight technical standards, so as to provide scientific reference for the large-scale development of plateau photovoltaic-pastoral complementary.

Keywords: Qinghai-Xizang Plateau; high-altitude pastoral area; photovoltaic-pastoral complementary system; ecological restoration; carrying capacity.

1. Introduction

1.1. Application Background

The 2022 national plan for large-scale wind and PV bases in desert, Gobi and arid areas targets roughly 455 million kW of installed wind and solar capacity by 2030, with 284 million kW slated for four major desert-based projects [1]. A circular development model has been advanced that pairs new energy expansion with ecological restoration alongside a closed-loop system linking power generation revenue to ecological investment and carbon sequestration gains [2]. The Qinghai-Xizang Plateau's high-altitude pastoral zones function doubly as a national ecological security barrier and as strategic locations for photovoltaic sand control coupled with new energy base expansion. In the inland basin of the Yellow River Basin, a feasibility study has been carried out on a large-scale integrated industry combining photovoltaic power generation and animal husbandry , while the concept of ' desert energy ecosystem ' emphasizes the coordination and unification of economic, social and ecological benefits [3,4].Grassland degradation affected by climate change and overgrazing must be addressed through zonal and classified restoration, balanced grassland and livestock resource management, and pastoralists ' participation in governance to enhance ecosystem service functions.

1.2. Fundamental Support for Collaborative Models and Restoration Technologies

Photovoltaic desertification control studies have put forward a photovoltaic-soil-vegetation coupling arrangement that elucidates positive feedback loops among shade-induced rainwater harvesting, wind dampening, sand blockage, and vegetation enhancement [5].Based on the component microhabitat system, the ecological suitability study of grassland photovoltaic systematically combed the energy-microclimate-soil-biological response chain, and pointed out the development direction of ' grassland photovoltaic + ' [6].Multi-scale ecological effect reviews have additionally traced impact pathways from micro-local through macro-regional to global levels, presenting a conceptual scheme for positive and negative externalities across full life cycles [7]. That photovoltaic arrays stimulate grass growth and natural vegetation recovery has already been demonstrated by the Longyangxia water-photovoltaic complementary project.

1.3. Main Challenges of High-Altitude Pastoral Photovoltaic Complementarity

The transplantation of photovoltaic-pastoral integration in high-altitude pastoral areas faces six constraints. First, the fragile ecological foundation: degradation has reduced aboveground biomass by 47.23% and soil organic carbon by 32.35% in alpine grasslands; fertilization alone cannot reverse

this degradation, and vegetation and soil deterioration reinforce each other[8]. Second, long recovery periods for vegetation: restoration between solar panels is better than under them, and disturbances only partially recover over time, requiring longer-term data to validate[9]. Third, difficulty in maintaining grassland-cattle balance: the cold-season carrying capacity in the Three-River-Source region is low, necessitating management based on digestible protein capacity, with calculation methods shifting toward multi-parameter dynamic assessments[10,11]. Fourth, insufficient localized technological support: array design, grass species selection, and grazing management standards suitable for high-altitude freeze-thaw environments remain inadequate. Fifth, strong spatial heterogeneity: observations in eastern plateau regions show that soil freezing periods have extended by approximately 50 days[12]. Sixth, uncertain long-term ecological impacts: after six years of construction, although soil nutrients increased, microbial α-diversity significantly declined, indicating coexistence of improved water and nutrient retention with increasing vulnerability of subsoil ecosystems[13].

1.4. Scope and Framework of This Review

Existing reviews have gravitated toward photovoltaic-pastoral integration in agriculture or toward photovoltaic sand control and ecological suitability in arid desert regions, leaving a conspicuous gap in comprehensive analyses directed at cold highland pastoral areas that knit together the full chain from processes to models, technologies, evaluation, and implementation [5]. The present review concentrates on integrated photovoltaic systems that unite natural grassland grazing, artificial forage cultivation, and ecological restoration, arranged according to a process-model-technology-zoning-engineering structure.

2. The System Connotation and Theoretical Basis of Photovoltaic-Pastoral Complementary

2.1. Core Objectives

The essence of photovoltaic-pastoral complementarity is to achieve ecological restoration, energy production and animal husbandry production in the same land unit. The systematic review shows that the coupling of power generation and agriculture in the same place can alleviate the " grain can compete for land, " and the reasonable light environment under the board and crop configuration are the key to coordination [5]. The ecosystem services perspective extends the goal to the food-energy-environment nexus[5, 14]. The first empirical reciprocal mechanism in the field experiment in semi-arid areas : shading reduces the temperature and water loss under the plate, and vegetation transpiration cooling feeds back photovoltaic efficiency [15].

2.2. Quartet method of system mode

According to the land use pattern and disturbance intensity, the current practice can be divided into four modes. Light grazing on natural grasslands can protect native vegetation while controlling livestock carrying capacity. Artificially planted forage grass achieves a land equivalent ratio of 1.33-1.68 under weak light conditions under solar panels by optimizing the mixed sowing combination of gramineous and leguminous plants [16]. The progressive ecological restoration classified by precipitation patterns reflects the principle of ' restoration first, then utilization ' [5]. The complex industry integrates photovoltaic power generation, animal husbandry and ecological management into a large-scale industrial system [3]. The four sand control models of ' desert energy ecosystem ' are highly corresponding to this classification [4].

2.3. Three kinds of values of ecology-economy-society

The three types of value weights change with the development model and are interrelated (Table 1). The " five-in-one " model incorporates the carbon sink gain into the economic closed loop, so that the ecological value can obtain an accountable economic export[2]. The economic income feeds back the ecological investment and the social participation supports the long-term management and protection, which constitutes the coupling structure of " ecological bottoming-economic driving-social maintenance. "

Table 1. Comparison of Ecological, Economic, and Social Value Dimensions of Photovoltaic-Pastoral Systems

Value Dimension	Core representation	Typical evidence	Mainly based on the model
Ecological value	Vegetation restoration, wind and sand control, and carbon sequestration enhancement	"Power generation revenue—ecological investment—carbon sequestration gain" closed-loop[2]; ecological coordination of four desert control models	Progressive ecological restoration and integrated industrial development
Economic value	Power generation revenue, livestock production, financial feasibility	22,000 hectares of pastoral base, approximately 5 million "photovoltaic sheep," internal rate of return of 6.66% to 7.59%	Integrated industrial and natural pasture-based grazing model
Social value	Pastoralists' employment and income growth, rural revitalization, and industrial integration	Integrated water and livestock development drives industrial integration in pastoral areas[3]; social benefits are coordinated through an ecosystem model.	Integrated industrial convergence type

2.4. System design and benefit trade-off

Array spatial parameters directly shape microhabitats. The soil moisture in Tengger base showed a pattern of ' front plate > behind plate > under plate ' [17]. Reasonable array spacing and the height of the lower edge of the plate can maximize the light received by the plants under the plate [5]. The triple benefit is not a natural synergy, and the ' drought mitigation potential ' hypothesis indicates that the photovoltaic

ecological gain depends on the degree of drought [18]. After 6 years of construction, soil nutrients increased but microbial communities degraded [13]. Benefit evaluation must include precipitation gradient and long-term time scale.

3. Vegetation-soil Ecological Response Characteristics and Driving Mechanism

3.1. Overview of the Path of Action

By shading, intercepting precipitation and weakening wind speed, photovoltaic modules reshape the gradient micro-habitat of ' front eaves-under-board-inter-board-outside the garden ' and change the surface energy distribution [19]. The annual gradient observation of the plateau shows that the net radiation of the photovoltaic power station is increased by 28.9 %, the wind speed is reduced by 36.2 %, the inter-plate is cold and wet, the under-plate is cold and dry, the soil freezing period is extended by 50 days, and the water loss in the non-freezing period is reduced by 1.3 ~ 3.5 times [12]. The reconstruction of photovoltaic microhabitat produces cascade ecological effects and drives the directional succession of vegetation-soil system [20].

3.2. Vegetation level response

After the construction of the station, the coverage of the tower beach increased by 83.9 %; the biomass between boards was significantly higher than that under and outside the board; the diversity of alpine meadow increased but the biomass decreased by 18.52% [21,22,23]. In terms of phenology, photovoltaic only delayed the withering period under the board for about 10 days, and had no significant effect on regreening. The community was reorganized in the eastern margin of the plateau for 4 years, the proportion of grasses increased and sedges decreased [23]. On the whole, the recovery between the plates is better than that under the plate, and gradually tends to be stable with the extension of operating years [9].

3.3. Soil-level response

In terms of water, the shading of high-altitude power stations in Tibet inhibits evaporation, and the soil moisture under the board is significantly increased [12]. The order of moisture gradient in Tengger is pre-plate > post-plate > under-plate ; the soil soil moisture of Talatan increased by 88.6 % [17, 21]. In terms of nutrients, the long-term operation of Gobi and sandy soil was comprehensively improved, and the improvement of 0-20 cm surface layer was the best [22]. Soil organic carbon and total nitrogen accumulated year by year ; the total phosphorus and available nutrients decreased in the eastern margin of the plateau for 4 years [22, 23]. In terms of microorganisms, organic matter increased and microbial alpha diversity decreased after 6 years of desert photovoltaic ; the accumulation of litter around the board forms a significant fertilizer island effect, and the nutrients are locally enriched [13,24].

3.4. Core Driving Path

(1) Microclimate regulation: shade cooling and evaporation reduction, vegetation transpiration reverse cooling photovoltaic modules in semi-arid areas; water availability under drought gradient is the core regulatory factor [15,18].

(2) Vegetation-soil fertilizer island feedback: litter accumulation around the board, local enrichment of nutrients to form a fertilizer island effect [24].

(3) Grazing biological regulation: moderate grazing inhibits the simplification of dominant species, and sheep can replace weeding machinery [25].

3.5. Drought gradient and grassland type difference

There were significant spatial differences in the response of photovoltaic vegetation and soil (Table 2). The ANPP of semi-arid grassland increased by about 20 % in dry years, and the edge of the plate was about 90 %, and the effect of wet years disappeared [18]. The vegetation differentiation in the arid desert (Tengger) is significant, the diversity of fixed and adjustable models is higher, and the soil moisture is dominated by the redistribution of array precipitation and the form of support. ; the recovery of desert steppe between boards is better than that under boards, and gradually recovers with years ; alpine meadow interplate ' cold wet ', under the plate ' cold dry ', freezing period is extended by about 50 days ; the alpine desert showed a nonlinear response along the extreme arid and semi-arid gradient[9,12,17]. There was no recovery in the extreme arid area and no relief in the heat island effect. The transpiration cooling in the semi-arid area offsets the warming. ; the biomass under the desert steppe increased by 104.1 %, and the withering period was delayed by about 10 days [21,26]. In general, the effect of shading and water conservation is more prominent under drought background, and the grassland type and drought background jointly determine the direction and intensity of response.

4. Mainstream Application Models and Practical Progress

4.1. Lightly Grazed Natural Grassland (Photovoltaic Sheep Model)

A representative case is the Talatan area in Qinghai, where photovoltaic arrays help block snow and reduce wind, thereby decreasing evaporation. Local humidity has increased by 3.87%, and grass growth within the site outperforms that outside [21]. Grass quality under the panels has improved, and sheep tend to spend most of their time in shaded areas, making moderate grazing a viable alternative to mechanical weeding [25]. Shortcomings remain, however, including the lack of quantitative standards for local livestock carrying capacity in high-altitude cold regions and for rotational grazing systems.

4.2. Artificial Forage Mixed Sowing Production Type

Mixed sowing of legumes and grasses is the optimal configuration, with a land equivalent ratio of 1.33 to 1.68 for high-altitude red clover combined with Elymus nutans [16]. This system requires a complete process including soil preparation, no-till seeding, field management, and mowing or grazing. The limitation lies in the lack of long-term trials on specific mixed sowing ratios tailored for permafrost-thaw zones.

Table 2. Comparison of photovoltaic ecological response characteristics under different grassland types / drought gradients

Grassland type/area	Vegetation response	Soil response	Dominant driving factors
Semi-arid grassland	ANPP increased by about 20% in dry years and reached approximately 90% at the board edge, with the effect of wet years disappearing.	Shading alleviates water stress	Precipitation regime and drought gradient
Arid Desert (Tengger)	Vegetation differentiation is significant, and the diversity of fixed-adjustable patterns is higher.	Soil moisture: "front of board > back of board > under board"	Array Precipitation Redistribution and Support Structure Configuration
Desert Steppe (Ningxia)	Recovery is better in the board area than under the board, gradually improving over time.	Ecological disturbance partially recovers over time.	Recovery period
High-altitude meadow (eastern Qinghai-Xizang Plateau)	Cold and humid above the board, cold and dry below the board	Freezing period extended by approximately 50 days	Freeze-thaw process and energy distribution
Cold desert (extremely arid to semi-arid gradient)	No recovery in extremely arid regions, rapid recovery in semi-arid regions	Heat island effect shows no relief in extremely arid regions; evapotranspiration cooling offsets warming in semi-arid areas	Drought gradient and water availability
Alpine meadow vs. desert steppe	Understory biomass in desert grasslands increased by 104.1%; the yellowing period was delayed by approximately 10 days.	The shading and water-retention effects are more pronounced under drought conditions.	Grassland types and drought background

4.3. Ecological Restoration + Progressive Livestock Grazing

For desertification and black soil patches, the approach involves first preventing wind erosion and stabilizing sand, improving soil quality, and then implementing low-intensity grazing once vegetation meets standards. Restoration pathways are categorized into three types: natural recovery, artificial grass planting, and drip irrigation combined with straw checkerboard (grass-grid) barriers [5]. The Tenggeri 6GW site has established an integrated restoration system [27]. The main shortcoming lies in the lack of quantified thresholds for transitioning from restoration to grazing in high-altitude cold regions.

Table 3. Comparison of Three Mainstream Photovoltaic-Pastoral System Models

Pattern	Degree of ecological disturbance	Operational maintenance cost	Output efficiency	Recovery cycle	Representative Practice
Lightly grazed natural grassland	Low, relying on the natural grassland's positive succession	Low, grazing as an alternative to mechanical weeding	Dual output of power generation and livestock products	Short, can be grazed and utilized in the same year	Talatan "Photovoltaic Sheep"
Artificial forage mixed sowing production type	In this area, artificial grassland needs to be established.	Higher, with significant investment required for cultivation and maintenance	Forage yield increased significantly, with LER ranging from 1.33 to 1.68	requires 1 to 2 growing seasons	High-altitude cold grassland legume-grass mixed sowing
Ecological restoration + progressive pastoralism	High, with concentrated engineering disturbances during the recovery period	High, with significant investment required in the repair technology system	Prioritize ecological benefits and gradually release the benefits of animal husbandry	Only after the grass has grown sufficiently and met the required standards can grazing be allowed.	Tengger 6GW Base[27], Grass Grids + Drip Irrigation

4.4. Adaptation and Modification of High-Cold Zone Models for Arid Regions

The mature photovoltaic models from Kubuqi and Tengger deserts cannot be directly applied here due to the combination of high-altitude conditions and long-term freeze-thaw cycles, which result in entirely different soil water retention mechanisms; thus, it is necessary to optimize array height, row spacing, cold-resistant grass species, and seasonal grazing systems.

5. Key Technical Systems and Optimization Methods

5.1. Photovoltaic Array Matching Design

Row spacing and support height are designed to balance light availability for forage growth with sheep passage; the flat single-axis, tracking system promotes vegetation recovery; construction minimizes site grading and reduces disturbance[5] to native soil. Current parameters are only suitable for low-altitude arid regions, with a lack of optimized standards for high-altitude areas affected by freeze-thaw cycles.

5.2. Grassland Vegetation Restoration Techniques

Select cold-tolerant native grass species such as Qinghai early maturing meadow grass and Elymus repens; implement differentiated mixed sowing with high-yield, sun-loving grasses between boards and shade-tolerant grasses under boards; adopt no-till, low-disturbance planting to minimize surface disruption[16].

5.3. Grazing Management Techniques

Shift from static livestock carrying capacity quotas to dynamic[11] multi-parameter calculations; the cold-season carrying capacity in the Three-River-Source region is low, with digestible protein as the benchmark[10]; implement zoned rotational grazing for photovoltaic areas, prioritizing use of spaces between and along panel edges while restricting grazing[25] under panels.

5.4. Soil Improvement and Water-Fertilizer Management

Relying on the natural water retention of board surface runoff collection; improving degraded soil with organic and microbial fertilizers; applying fertilizers to balance soil fertility and species diversity, avoiding reduced richness due to excessive use of single nitrogen fertilizers [8].

5.5. Intelligent Monitoring and Optimization Methods

Drones, Sentinel remote sensing, and UNet (U-shaped network) deep learning enable precise identification of photovoltaic zones and vegetation [28]; structural equation models and BRT (Boosted Regression Trees) quantify driving factors; a hybrid model combining mechanistic understanding with machine learning addresses poor generalization of pure data-driven approaches [7].

Table 4. Summary of Key Technologies for Photovoltaic-Pastoral Complementarity

Technical Category	Core content	Key Points for High-Altitude Adaptation
Photovoltaic Array Compatibility Design	Optimization of line spacing and board bottom elevation, selection of support structure type, and low-disturbance construction	Parameter adaptation to freeze-thaw hydrothermal patterns and grazing accessibility
Grassland vegetation restoration	Selection of native stress-tolerant grass species, mixed sowing of grasses and legumes, and differentiated configuration	Core germplasm of Qinghai early maturing meadow grass and Elymus nutans
Grazing management	Carrying capacity threshold calculation, multi-parameter dynamic accounting, and rotational grazing by zones	Low cold-season carrying capacity, based on digestible protein
Soil Improvement and Water-Fertilizer Management	Rainwater harvesting and water conservation, combined with nitrogen and phosphorus application plus enclosure and crust improvement	Soil fertility enhancement constrained by biodiversity conservation
Intelligent optimization methods	Remote sensing monitoring, deep learning recognition, hybrid modeling	"Space-Air-Ground" integrated observation supporting online calibration

6. Ecological Zoning Adaptation and Suitability Assessment

6.1. Evaluation Core Metrics and Models

The evaluation indicators include ecological sensitivity (modeled using four factors: topography, soil, climate, and ecology), construction suitability, drought gradient, grassland carrying capacity, and vegetation cover. The evaluation model employs SOFM (Self-Organizing Feature Map) clustering, a coupling coordination degree model, and GIS-based multi-factor overlay analysis. In Qilian County, the coupling coordination method was used to complete a four-level zoning[29] classification.

6.2. Three-Level Gradient Zoning Scheme

(1) Semi-arid alpine meadow: high ecological sensitivity, priority for protection, suitable for light rotational grazing;

(2) Arid desert grassland (Talatan type): significant ecological benefits from photovoltaic projects; suitable for both natural grazing and artificial mixed seeding.

(3) Extremely arid desert: vegetation restoration is difficult, with ecological rehabilitation as the primary approach and strict restrictions on grazing intensity.

6.3. Deficiencies in the Current Evaluation System

Partitioning results are highly influenced by models; indicators for freeze-thaw and seasonal permafrost are missing; microhabitats, county-level, and regional scales are fragmented; and remote sensing monitoring lacks unified evaluation standards.

Table 5. Differences in Objectives and Evaluation Criteria for Various Applications of Photovoltaic-Pastoral Integration

Application scenarios	Core Objective	Main assessment content	Technical standards focus on
Ecological restoration	Restoration of Degraded Grassland Vegetation–Soil Function	Vegetation cover, community diversity, and recovery of soil physicochemical properties	Constrained by ecological thresholds
Livestock production	Forage production and enhanced efficiency in livestock farming	Forage yield, carrying capacity, financial return rate	Quantitative assessment of output and revenue
Rural Revitalization	Herdsmen 's income and livelihood improvement	Employment absorption, income distribution, ecological compensation implementation	Institutional arrangement and distribution mechanism
Carbon sink development	Carbon sequestration and carbon capitalization of grassland	Carbon sink measurement, monitoring and certification	Accountable carbon closed loop

7. Conclusion and Foresight

The existing research has laid a preliminary scientific foundation for the integration of photovoltaic-agriculture and animal husbandry in the Qinghai-Xizang Plateau from four dimensions. (1) Mechanism-photovoltaic array reshapes microhabitats through shading, precipitation redistribution and wind attenuation, and the vegetation-soil response changes nonlinearly along the drought gradient. (2) The model-four mainstream types (light grazing, artificial pasture, progressive restoration, compound industry) were verified in Talatan, Tengger and Qilian counties. The land equivalent ratio was 1.33 ~ 1.68, and the internal rate of return was 6.66 % ~ 7.59 %. (3) The technical framework adapted to the alpine environment was formed by technology array optimization, native grass species screening, dynamic carrying capacity calculation and rotational grazing. (4) The evaluation-coupling coordination zoning method is becoming more and more mature, and the four-level adaptive zoning is realized. At the same time, a multi-scale impact framework from micro to global scale is initially established.

There are still four major gaps, which correspond to the deficiencies identified in section 6.3. The current zoning results rely heavily on model-driven assessments and lack sufficient field verification; therefore, future research should establish a long-term fixed monitoring network covering the main alpine grassland types to achieve space-air-ground integrated observations to verify the model output and provide a solid data base. The evaluation index still lacks freeze-thaw and seasonal permafrost parameters; it is necessary to carry out multi-factor coupling experiments involving photovoltaic layout, grazing density and precipitation gradient to identify key thresholds under different grassland types. Assessments at the microhabitat, county and regional scales are still fragmented; by combining the ecological process model with the machine learning algorithm, a cross-scale comprehensive benefit evaluation model with both interpretability and prediction accuracy can be constructed. Remote sensing monitoring is still lack of unified evaluation criteria; the establishment of a technical specification and standard system covering the whole life cycle of photovoltaic animal husbandry integration, including site selection, construction, operation and maintenance, will promote the transformation of the project from pilot demonstration to large-scale standardization development. At the same time, low-cost monitoring equipment, no-tillage planting technology and precision grazing management technology should be developed to reduce the obstacles to project implementation in alpine regions.

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