Innovation and Practice of Biodiversity Conservation in Sanjiangyuan National Park: Postprint

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Abstract

Sanjiangyuan National Park is one of the first batch of national parks officially established in China and also the largest national park in the country. As an important ecological security barrier and plateau biological germplasm resource bank for China, it holds significant conservation value both nationally and globally. To address a series of ecological conservation issues in Sanjiangyuan National Park—including biodiversity loss, destruction of wildlife habitats, degradation of alpine grasslands, and overgrazing by livestock—based on theoretical innovations in multi-functional objective management of grasslands and research and development of new technologies for biodiversity conservation, the implementation of major ecological conservation and restoration projects has been promoted, forming a new paradigm of scientific and technological support for biodiversity conservation and livelihood improvement in Sanjiangyuan National Park. This provides practical solutions for China' s ecological civilization construction, offers Chinese wisdom for global national park development, and presents Chinese solutions for global biodiversity conservation.

Full Text

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Abstract

Sanjiangyuan National Park is one of the first batch of national parks formally established in China and also the largest national park in the country. As a critical ecological security barrier and alpine biological germplasm resource bank, it holds significant conservation value both nationally and globally. Addressing a series of ecological protection issues in Sanjiangyuan National Park—including biodiversity loss, wildlife habitat destruction, alpine grassland degradation, and livestock overgrazing—this study promotes the implementation of major ecological protection and restoration projects based on theoretical innovations in grassland multifunctional target management and the development of new biodiversity conservation technologies. This effort has forged a new paradigm of scientific and technological support for biodiversity conservation and livelihood improvement in Sanjiangyuan National Park, providing practical solutions for China' s ecological civilization construction, Chinese wisdom for global national park development, and Chinese solutions for worldwide biodiversity conservation.

Keywords: grassland multifunctionality, biodiversity conservation, rewilding, grassland-livestock balance, national park

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1. Biodiversity Conservation in Sanjiangyuan National Park: Problems and Challenges

Located in the hinterland of the Qinghai-Tibet Plateau, the Sanjiangyuan region serves as the source of the Yangtze, Yellow, and Lancang Rivers, representing a global biodiversity hotspot and a vital ecological security barrier for China. To protect the region' s unique alpine ecosystems and biodiversity, the General Office of the Communist Party of China Central Committee and the General Office of the State Council issued the *Sanjiangyuan National Park System Pilot Scheme* in March 2016, establishing Sanjiangyuan as China' s first national park pilot. In 2021, it became one of the first national parks formally established in China, covering a total area of 19.07$×10^{4}$ km^2. The park is rich in natural resources, with a total grassland area of 13.25$×10^{4}$ km^2 and forest area of 495.95 km^2. It hosts 832 species of seed plants and 310 species of wild animals, most of which are endemic to the Qinghai-Tibet Plateau with large populations, earning it the title "Wildlife Kingdom on the Plateau."

Due to its unique geographical location and landforms, the region' s ecosystems are extremely fragile and highly susceptible to climate change and human disturbances. The soil layers are young and infertile, with weak erosion resistance, slow plant growth, low productivity, and ecosystems in early developmental stages characterized by instability and dramatic fluctuations. Additionally, under the influence of global climate change and human activities, warming and localized wetting trends have caused glacier retreat, snow melt, reduced river runoff, soil erosion, grassland degradation, and land desertification. Grassland degradation is accompanied by loss of plant diversity, which alters the habitat environment for wild herbivores, leading to habitat fragmentation, islandization, declining populations of key species, and threats to biodiversity. These challenges affect the delivery of ecological services, including biodiversity conservation, in the Sanjiangyuan region.

Since the launch of the national park pilot, addressing existing biodiversity conservation problems and based on the multifunctionality of grasslands in the Sanjiangyuan region and the protection of ecosystem authenticity and integrity, we have explored and formed a new paradigm of scientific and technological support for biodiversity conservation in Sanjiangyuan National Park. This paradigm encompasses "conceptual innovation, theoretical breakthroughs, technological advances, integrated models, demonstration and promotion, and collaborative development," providing practical pathways for China' s ecological civilization construction, valuable lessons for international biodiversity conservation, and support for the construction of nature reserve systems with national parks as the mainstay.

2. Integration with International Biodiversity Conservation Plans: Conceptual Framework

The Sanjiangyuan region is one of the world' s most biodiverse areas, with its geographical location and unique topography determining its rich ecosystem diversity, species diversity, genetic diversity, and natural landscape diversity [1]. According to the Sanjiangyuan National Park Master Plan (2023–2030), the park contains 832 seed plant species belonging to 50 families and 231 genera, and 310 wild vertebrate species belonging to 32 orders and 75 families, including 62 mammal species in 8 orders and 19 families, 196 bird species in 18 orders and 44 families, 7 amphibian species in 2 orders and 5 families, and 5 reptile species in 1 order and 3 families, constituting a precious germplasm and highland gene bank.

Halting grassland ecological degradation, restoring degraded grasslands, and protecting wildlife habitats have become critical issues for maintaining ecosystem authenticity and integrity and conserving biodiversity in Sanjiangyuan National Park. The region' s ecosystems are extremely fragile, and under global climate change and human disturbance, trends toward warming and localized wetting have caused glacier retreat, snow melt, reduced river runoff, soil erosion, grassland degradation, and land desertification. Grassland degradation is accompanied by plant diversity loss, altering wild herbivore habitats, causing habitat fragmentation and islandization, declining key species populations, and threatening biodiversity, which challenges wildlife habitat environments and affects the delivery of biodiversity-related ecological services in the Sanjiangyuan region.

The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) and the Intergovernmental Panel on Climate Change (IPCC) have jointly emphasized in workshop reports that biodiversity loss and global climate change pose inseparable threats to human health and development, requiring an integrated approach to address them synergistically. The World Wide Fund for Nature (WWF) *Living Planet Report 2022* indicates that the Living Planet Index (measuring the average decline in vertebrate populations) has dropped by an average of 69% since 1970, underscoring the urgency of building a nature-positive society. Consequently, the Kunming-Montreal Global Biodiversity Framework has emerged, aiming to take broad-based actions to transform society' s relationship with biodiversity and ensure the shared vision of "living in harmony with nature" by 2050, while providing programmatic guidance for the Convention on Biological Diversity and other biodiversity-related multilateral agreements, processes, and instruments, and promoting implementation of the 2030 Agenda for Sustainable Development.

A critical prerequisite for achieving a nature-positive society is respecting the rights of indigenous peoples and local communities worldwide, while important pathways for mitigating the dual crises of climate change and biodiversity loss include enhancing environmental protection and natural restoration levels, promoting sustainable food production and consumption, and rapidly advancing decarbonization across all industries. During the pilot phase of Sanjiangyuan National Park' s institutional mechanism, considerable emphasis was placed on aligning with international biodiversity conservation plans. Centering on problems among biodiversity conservation, ecological restoration, and high-quality development, we innovatively developed the theory of grassland multifunctionality, clarified new pathways for achieving multifunctional objectives [2], developed new technologies for species conservation and regional development, and proposed two new development concepts: a demonstration and promotion paradigm combining scientific research with engineering practice, and a harmonious development model integrating biodiversity conservation with sustainable pastoral livelihoods, providing successful cases for global biodiversity conservation that are replicable and instructive.

3. Reconsidering Grassland Functions and Multifunctional Target Management: Theoretical Framework

With rapid societal development, improving living standards, and evolving social contradictions, perceptions of grassland functions have also changed. In the new era, beyond traditional livestock production functions, grasslands' regulatory, provisioning, supporting, and cultural functions have gradually been explored and utilized. Among grassland ecological service values, managers focus most on two attributes: grassland biodiversity conservation and natural resource attributes. Sanjiangyuan National Park integrates biodiversity conservation, grassland service functions, and aesthetic values. Through the construction and practice of Sanjiangyuan Nature Reserve and National Park, we have built a new-era grassland multifunctional target management framework that optimizes spatial layouts of protected grasslands, grazing grasslands, and cultivated grasslands to achieve multifunctional management objectives (Figure 1); scientifically 核定 grazing grassland carrying capacity to realize sustainable grassland resource utilization; expanded cultivated grassland establishment according to local conditions to create new models of modern and regional grassland-animal husbandry production, breaking through seasonal and regional nutritional imbalance bottlenecks in alpine grassland-animal husbandry; implemented demonstration projects for balanced management of grazing livestock and local wild herbivores in protected areas, practicing the concept of a community of life between humans and nature; and implemented new compensation standards based on "opportunity + management" costs, seeking new compensation mechanisms based on protection effectiveness to address unbalanced and insufficient regional resource allocation [6].

The theoretical foundation of the grassland multifunctional target management framework encompasses ecosystem ecology, biodiversity, trophic levels (food webs), nutritional imbalance, nutritional niches, intermediate disturbance, fitness, rewilding, and optimal resource spatial allocation theories [4,5]. The technical system includes precision ground information measurement and remote sensing inversion, grazing rate and carrying capacity measurement based on grassland biomass accumulation, forage breeding technologies, forage planting-processing and livestock nutritional balanced feeding, biodiversity maintenance and resource protection and utilization, ecological function enhancement, and ecological product value realization. The management models cover green development indicator systems, regional coupling of climate-biological-capital resources, balanced management of ungulate wildlife and grazing livestock, and modular dynamic models for grassland multifunctional target management [4].

4. Research and Application of New Biodiversity Conservation Technologies

Protecting the ecological environment on which plateau organisms depend is the primary task for conserving Qinghai-Tibet Plateau biodiversity. Through new technology research and application in wildlife monitoring, habitat assessment, ecological corridor planning, carrying capacity 核定, ecological restoration, high-quality forage planting and processing, and livestock nutritional balanced breeding in Sanjiangyuan National Park, we have achieved precision management and technological breakthroughs in biodiversity conservation (Figure 2).

4.1 Animal Aerial Monitoring Platforms and Technological Innovations

(1) Multi-UAV collaborative survey of Tibetan antelope populations. Traditional surveys of Tibetan antelopes in the 6 km^2 calving area around Zhuonai Lake in Hoh Xil required 4–6 days to complete flight operations. Through collaborative optimization with four UAVs, the time was reduced to 2 hours, obtaining image data of approximately 6×10^{4} Tibetan antelopes—the most complete documentation of high-density populations in a small area discovered to date [8].

(2) Tethered balloon aerial monitoring platform. For the first time, tethered balloons were used for ground observation operations above 4,600 m elevation, employing thermal infrared sensing equipment to monitor Tibetan antelope nocturnal behaviors, obtaining data on nighttime feeding, resting, migration, and mating activities [9]. At 150 m altitude, the balloon can monitor large wildlife within a 2–5 km range, with temperature resolution greater than 0.1°C and ground resolution of 3–5 cm, providing innovative technical support for wildlife behavior research and population surveys.

(3) Helicopter-mounted photoelectric pods and spheres. The pods and spheres can carry visible light, medium-wave infrared, polarized light, LiDAR, and hyperspectral equipment, achieving ground visible light resolution of 5–7 cm, hyperspectral imager resolution of 30 cm, and endurance of 500 km, offering advantages in comprehensive monitoring (animals, vegetation characteristics, topography, and water resources).

(4) Satellite remote sensing monitoring. Using high-resolution remote sensing satellites to observe large sample plots, we obtain high-resolution remote sensing data in pilot areas. Based on high-precision remote sensing biodiversity monitoring and evaluation methods, we extract wildlife population information to form regional wildlife population distribution control data. When remote sensing image resolution is equal to or higher than 0.12–0.25 m, combined with geographic feature information and deep learning methods, we can determine large ungulate wildlife numbers and distribution. Monitoring calculations show that within the 2.3$×10^{4}$ km^2 core protection area of the national park, Tibetan antelope, Tibetan gazelle, and wild ass populations number 37,000, 34,000, and 17,000 individuals respectively, with densities greater than ground transect monitoring data. We have determined that the dry matter biomass of forage in Sanjiangyuan National Park is 516.78 kg/hm^2, livestock biomass is 3.61 kg/hm^2, wild herbivore biomass is 1.52 kg/hm^2, and carnivore biomass is 0.017 kg/hm^2 (Figure 3), indicating a stable trophic structure and a complete food chain in the park’ s grassland ecosystem.

(5) AI identification of herbivores from aerial images. Processing UAV images through grayscale conversion, Gaussian filtering, binarization, and detection, we automatically obtain population numbers and spatial distributions of major large herbivores with over 90% accuracy [10].

4.2 Endangered Animal Habitat Assessment and Ecological Corridor Planning in National Parks Habitat fragmentation impedes communication among conspecific populations in different habitat patches, increasing extinction risks from inbreeding and genetic drift, and limiting species’ ability to respond to long-term environmental changes. Therefore, maintaining and restoring landscape connectivity is crucial for wildlife conservation, particularly for species with severely fragmented habitats. Establishing migration corridors enhances habitat connectivity and maintains interpopulation dispersal and gene flow [11]. Based on wildlife baseline surveys and species distribution sites from literature, we collected 77 environmental variables across four categories, selected relevant variables to build models, and determined high, medium, low, and unsuitable areas for flagship species. For species migration resistance surfaces and corridor construction, we used core protection areas (suitable distribution zones) as corridor “sources,” with the lowest cumulative cost routes between nodes designated as migration corridors. Based on this approach, we mapped wildlife distributions for Tibetan antelope, wild ass, and Tibetan gazelle, assessed habitat suitability for 10 species including snow leopards and Tibetan antelope, and designed appropriate migration corridors.

4.3 Technological Innovation in Grassland Grazing Carrying Capacity 核定 Based on principles of grassland production science and animal nutrition science, we calculated seasonal dynamics of forage yield and nutritional quality in typical alpine grasslands, as well as feed intake and nutritional requirements of different herbivores. Referencing the *Technical Specification for Grassland-Livestock Balance Evaluation* (LY/T 3320-2022) and considering natural grassland degradation status and management objectives, we formulated grassland grazing utilization rate standards to 核算 herbivore carrying capacity. By analyzing factors influencing herbivore impacts on grassland carrying capacity, we conducted scientific and refined carrying capacity 核定. We calibrated grazing livestock numbers into sheep units based on livestock sheep unit conversion coefficients, quantified contributions of ungulates and rodents to grassland carrying capacity, determined the contribution of cultivated grasslands to grassland-livestock balance based on seasonal dynamic forage supply from ground monitoring and remote sensing correction data, and weighed the impacts of production methods on carrying capacity [7]. This research provides data support for grassland management in the Sanjiangyuan region, with 核定 carrying capacities of 0.58 and 0.21 SHU/hm^2 for the Sanjiangyuan region and Sanjiangyuan National Park, respectively.

4.4 Nutritional Balance Management for Grazing Livestock in General Control Zones of National Parks Based on precise 核定 of herbivore carrying capacity in alpine grasslands under different scenarios, we reduce grassland pressure and enhance ecological functions through optimal allocation of natural grasslands, implementing spring green-up period rest, rational grazing utilization, rotational grazing, and moderate winter supplementation, thereby providing space for wildlife reproduction and survival. During the spring green-up period, livestock are temporarily penned to promote vegetation growth; during summer peak growth, rational grazing improves utilization efficiency; during autumn reproductive growth, rotational grazing protects reproduction and seed banks; during winter dormancy, moderate supplementation improves livestock survival rates and health. Implementing green-up period rest technology in the Sanjiangyuan region has achieved grassland community height of 8.13 cm, coverage of 95.81%, aboveground biomass of 379.51 g/m^2, and underground biomass of 2,791.32 g/m^2. Applying nutritional balanced feeding technology for Tibetan sheep and yaks has shortened feeding cycles.

4.5 High-Yield Forage Cultivation and Processing in National Park Peripheral Support Zones Utilizing farmland, light, and heat resources in agricultural areas and agro-pastoral transition zones, and considering interspecific differences in soil nutrient requirements and ecological niches among different forage crops, we conducted mixed and intercropping of different forages (grasses and legumes), with weed control during seedling stages to increase high-quality forage supply. Based on grazing livestock nutritional requirements, we exploited synergistic effects among different forage combinations and livestock digestive utilization potential, processing different forages through combination, crushing, and silage fermentation to produce series products including hay, hay blocks, pellets, and baled silage, providing quality forage support for grazing livestock within the national park. Widely applied in peripheral support zones such as Batang Beach in Yushu City, Nangqian County, Maduo County in Guoluo Prefecture, and Guinan, Xinghai, and Tongde counties in Hainan Prefecture, this approach has established 6.7×10^{4} hm^2 of high-quality artificial grassland, producing 6.1×10^{4} t of forage annually, achieving a basic balance of grass-wild herbivore-livestock in the national park.

5. Biodiversity Conservation Practice Models in Sanjiangyuan National Park

(1) Integrated sky-space-ground ecological monitoring system and application. Integrating all relevant wildlife survey research results from the Sanjiangyuan region over the past decade, we established a sky-space-ground integrated wildlife survey method based on ground surveys of transects-quadrats-sample points, combined with new technologies such as UAVs, infrared cameras, and satellite remote sensing. We completed baseline wildlife surveys in Sanjiangyuan National Park and established a wildlife species database, compiling a wildlife species catalog containing 270 terrestrial wild vertebrate species belonging to 4 classes, 29 orders, and 72 families, including 62 mammal species in 8 orders, 19 families, and 44 genera; 196 bird species in 18 orders, 45 families, and 121 genera; 7 amphibian species in 2 orders and 5 families; and 5 reptile species in 1 order and 3 families. The park hosts 203 protected species, accounting for approximately three-quarters of all species, including 16 and 42 species under national first-class and second-class protection respectively, 142 species with beneficial, important economic, or scientific research value, and 30 provincial-level protected species [14].

(2) Endangered animal habitat evaluation and conservation model. Integrating suitable habitat evaluation technology and ecological corridor design technology, we constructed a biodiversity conservation model of "survey-monitoring-habitat suitability-habitat connectivity." Using the national park wildlife species database, geographic information system (GIS) spatial analysis, and remote sensing image interpretation, we overlaid and analyzed different strategies based on protection levels and carrying capacity, producing a set of 10 protection species distribution maps. We analyzed and evaluated suitable habitat distribution ranges for eight rare and endangered wildlife species including Tibetan antelope, wild ass, wild yak, Tibetan gazelle, snow leopard, saker falcon, Himalayan vulture, and upland buzzard, planned six distinctive eco-tourism experience zones, and designed seven Tibetan antelope migration corridors to increase habitat connectivity, with flagship species populations continuing to rise. This provides a basis for identifying, protecting, and restoring potential habitats for rare wildlife in the park and data support for national park boundary adjustments.

(3) Species rewilding model in Sanjiangyuan National Park. In and around Sanjiangyuan National Park, based on theories of nutritional niches, population dispersal capacity, intermediate disturbance, and optimal resource spatial allocation, we optimized spatial layouts of different grassland types, reconciled nutritional niches between livestock and wild herbivores, improved wildlife population carrying capacity, and optimized ecological, production, and living functions for biodiversity conservation, forming a "protected area rewilding model" targeting biodiversity conservation. In surrounding areas, transitioning from seed-based agriculture to vegetative agriculture established 6.7×10^{4} hm^2 of high-quality artificial grassland, producing 6.1×10^{4} t of forage annually, achieving a grass-wild herbivore-livestock balance in the national park. Establishing livestock production transfer and undertaking zones in surrounding areas developed efficient animal husbandry, implementing demonstration projects for balanced management of herbivores and livestock, transferring 810,000 sheep units of livestock and expanding ungulate wildlife habitat by 3.85×10^{4} km^2, achieving a "win-win" for ecological protection and livestock production.

(4) Dual enhancement model of alpine grassland ecological and production functions. Alpine grassland natural landscapes and community structures result from co-evolution between grazing livestock, herbivorous wildlife, and grassland vegetation, forming plagioclimax communities under long-term grazing and wild herbivore browsing. Integrating technologies for grassland carrying capacity 核定 and early warning, herbivore population dynamic monitoring, and sustainable grassland utilization, we formed a "rational utilization model for alpine grassland based on authenticity maintenance," monitoring interannual and seasonal herbivore carrying capacity dynamics to determine critical overgrazing thresholds, providing fundamental guidelines for regional grassland management. Over 20 years, grassland productivity has gradually increased and stabilized. Implementing ecological restoration technologies on degraded alpine meadows, classified intervention restoration technologies on black soil mountains (slopes), and degraded alpine grassland ecological restoration technologies, we formed a near-natural restoration system combining native grass species mixed sowing + no-tillage supplementary sowing + biochar + functional bacterial fertilizer + growing season rest, integrating the "Sanjiangyuan grassland ecosystem service function enhancement model" [12]. This has treated 71×10^{4} hm^2 of severely degraded alpine grassland, established 291×10^{4} hm^2 of grazing withdrawal and forage bases, increased vegetation coverage to over 70%, and achieved aboveground biomass of 4.5–7.5 t/hm^2. Regional water conservation, soil retention, and windbreak and sand fixation have reached 742 m^3/hm^2, 28.4 t/hm^2, and 22.44 t/hm^2 respectively, all showing increasing trends [3]. Over the past 20 years, net ecosystem productivity in the Sanjiangyuan region has continued to increase, with a multi-year average of 0.37 t/hm^2 and annual carbon sequestration potential of approximately 8.4×10^{6} t [14].

6. Integration of Scientific Research and Major Ecological Protection Projects: Demonstration and Promotion

(1) Practice of new biodiversity conservation models. By promoting the "survey-monitoring-habitat suitability-habitat connectivity" biodiversity conservation model, the IUCN Red List adjusted the Tibetan antelope status from "endangered" to "near threatened" in 2016, and the snow leopard from "endangered" to "vulnerable" in 2017. Brown bears, wolves, and small felids have become commonly observed, food chains and food webs have become more complete, and ecosystem complexity and stability have significantly increased (Figure 3). Populations of Tibetan antelope, Tibetan gazelle, wild ass, wild yak, and white-lipped deer in Sanjiangyuan National Park have reached 60,000, 60,000, 36,000, 10,000, and 10,000 individuals respectively (Figure 4), while carnivores mainly include snow leopards, brown bears, red foxes, Tibetan foxes, Pallas' s cats, Chinese mountain cats, and saker falcons, with Tibetan foxes, Pallas' s cats, and Chinese mountain cats numbering 20,000, 20,000, and 10,000 individuals respectively [15-17].

(2) Implementation of grassland-livestock balance management projects in Sanjiangyuan National Park. Supporting the construction of peripheral support zones (production undertaking zones) transfers overloaded livestock outside the park, achieving optimized regional resource allocation between "protection" and "production" functions [19]. In Tongde, Guinan, and other areas in eastern Sanjiangyuan, establishing forage bases has strengthened the grass industry and facilitated rapid transition from seed-based to vegetative agriculture, breaking seasonal nutritional supply-demand bottlenecks in grassland animal husbandry and effectively addressing overloading and overgrazing issues in the national park, providing demonstration models for resolving "human-livestock-land" contradictions in Qinghai-Tibet Plateau national park construction.

(3) Creation and demonstration application of grassland multifunctional management models. Based on differentiated natural resource endowments and multifunctional characteristics, we created grassland multifunctional management models (Figure 5) and applied them at scale in the Sanjiangyuan region and surrounding areas. This achieved efficient coupling of different grassland types in the region, incubated grassland animal husbandry projects such as Qinghai Province' s "breeding in the west, raising in the east; breeding at high altitude, raising at low altitude," and constructed a new plateau grass-animal husbandry production paradigm of "protecting large areas through small-scale development and reducing pressure to increase efficiency," advancing grassland animal husbandry development in the Sanjiangyuan region to new levels.

(4) Submitting consultation recommendations to provide scientific support for national strategies and policy formulation. Our team submitted *Consultation Recommendations on Ecological Protection and Sustainable Development in the Sanjiangyuan Region* [18,19] and *Grassland Construc-*

tion Achievements, Problems, and Recommendations, which received decision-makers'attention and were incorporated into the *Sanjiangyuan Ecological Protection and Construction (Phase II) Project* and Qinghai Province's 13th Five-Year Plan. The proposal for establishing the "Hainan Prefecture National Sustainable Development Agenda Innovation Demonstration Zone" was approved by the State Council. Twelve consultation recommendations and reports promoted the formal establishment of Sanjiangyuan National Park, the *National Grassland Ecological Animal Husbandry Pilot Zone*, the *Grassland Ecological Protection Subsidy and Reward Mechanism*, and the *Grazing Withdrawal and Grassland Restoration Project*, providing scientific foundations for implementing various ecological protection and restoration projects in similar regions.

7. Integration of Biodiversity Conservation and Herdsmen' s Sustainable Livelihoods: Harmonious Development

(1) Developing "protecting large areas through small-scale development and reducing pressure to increase efficiency" system solutions to improve grassland production efficiency. We created and demonstrated a "three-zone coupling" model integrating rational natural grassland utilization and livestock breeding in alpine grazing areas, forage production and intensive farming in agro-pastoral transition zones, and efficient utilization of agricultural and sideline products in valley agricultural zones. Promoting the establishment of 6.7$\times10^{4}$ hm^2 of high-yield artificial grassland producing 6.1$\times10^{4}$ t of quality forage annually has solved winter forage supply problems for 4 million sheep units, increased annual livestock marketing by 2.15 million sheep units (accounting for 30% of the Sanjiangyuan region' s livestock marketing), and effectively reduced grazing pressure on natural grasslands while enhancing livestock snow disaster resistance.

(2) Five "biodiversity conservation+" new technologies for multi-pronged, multi-stakeholder species diversity conservation. These include "biodiversity conservation + ecological animal husbandry," "biodiversity conservation + habitat restoration," "biodiversity conservation + forage industry," "biodiversity conservation + wild herbivore and livestock balance," and "biodiversity conservation + food web trophic complexity" technologies (Figure 6). We established 38$\times10^{4}$ hm^2 of forage production demonstration bases and two nutritional balanced livestock breeding bases for cattle and sheep, with 750,000 head of healthy livestock. Cumulative sales revenue from improved forage varieties and nutritional balanced feeding reached 237 million yuan, effectively promoting grassland ecological function restoration, transformation of grassland animal husbandry production methods, and economic benefits in the Sanjiangyuan region [7,20]. This effectively supported Sanjiangyuan National Park construction, promoted ecological function restoration, subsequent industrial development, biodiversity conservation, and social harmony and stability in the Sanjiangyuan region, accelerated industrial restructuring and livestock product value-added technology development, encouraged local herders to participate in ecological protection, transformed traditional production and lifestyle patterns, and guided herders toward poverty alleviation and rural revitalization, achieving win-win outcomes for regional biodiversity conservation and economic-social development.

(3) Exploring new ecological compensation mechanisms based on authenticity protection effectiveness. Following compensation principles based on "opportunity cost + management cost," we 核定 livestock numbers within the national park according to regional theoretical carrying capacity as the grazing pressure upper limit, transferring overloaded livestock to peripheral support zones outside the park [6]. The *Pilot Recommendations on Wildlife-Livestock Competition for Grassland and Compensation in Sanjiangyuan National Park* implemented two phases of compensation pilots in 13 administrative villages of Sanjiangyuan National Park, investing nearly 20 million yuan to address unbalanced and insufficient regional resource allocation, reduce human grazing impacts on wildlife, and effectively mitigate grassland competition between livestock and wild herbivores and human-wildlife conflicts, helping achieve coordinated ecological protection and livelihood improvement and promoting harmonious human-nature development.

(4) Empowering national park construction with digital technology and expanding big data applications. Based on the park' s natural endowments and construction functions, we established an ecological environment IoT monitoring platform for ecology and environmental monitoring using digital technology, achieving data transmission, management, and real-time online display. We established four long-term monitoring plots in the national park' s core protection area, achieving all-weather monitoring and real-time data transmission of meteorological, hydrological, and biological elements [21]; built a patrol management platform for 17,000 ecological rangers in Sanjiangyuan National Park, integrating ecological management and monitoring functions; created a digital product management and display platform for research, management, and decision-making departments to share data achievements; and produced 72 sets of 3D augmented reality (AR) digital models of key flora and fauna and four sets of virtual reality (VR) national park ecological environment scenario experience models, building a natural landscape experience platform for the public to further realize the park' s natural, cultural, and aesthetic values and achieve universal sharing.

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Note: Figure translations are in progress. See original paper for figures.