Postprint: Vulnerability Assessment Indicator System for Desertification Reversal Processes Based on Social-Ecological Systems

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Abstract

Land desertification is one of the most severe ecological and environmental problems in the world today. As its reverse transformation process, desertification reversal exhibits certain vulnerability and instability—that is, the tendency for the reversal trend to weaken or develop in the opposite direction. The social-ecological system concept represents a new approach to ecosystem analysis in the contemporary world. From this perspective, we define the concept of vulnerability in the desertification reversal process, adopt the Driving-Pressure-Status-Impact-Response (DPSIR) analytical framework, and select Yanchi County in Ningxia—a typical desertification reversal region in the agro-pastoral ecotone—as a case study. In accordance with the causal relationships and process characteristics of desertification reversal, we construct a four-layer, five-element, 41-indicator evaluation system encompassing the climate humidity index, ecological governance index, and proportion of sandy land. We then explore the logical causal relationships among the five elements of driving force, pressure, status, impact, and response, as well as the quantitative calculation method for vulnerability, aiming to scientifically assess the vulnerability of the desertification reversal process and provide a scientific basis for further governance and regulation of desertification issues in such regions.

Full Text

An Evaluation Index System of Vulnerability of the Desertification Reversion Process Based on the Socio-Ecological Systems Theory

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Abstract

Land desertification is one of the most severe ecological and environmental problems worldwide. Desertification reversion, as the reverse process of desertification expansion, exhibits certain vulnerability and instability—that is, a tendency for the reversal trend to weaken or reverse direction—due to disturbances from numerous socio-ecological factors. We term this phenomenon "vulnerability of the desertification reversion process" and define it as the possibility and tendency of a declining or reversing reversal trend. Socio-ecological systems theory represents a new approach to ecosystem analysis. From this perspective, we selected the Driving-Pressure-Status-Impact-Response (DPSIR) framework and Yanchi County, a typical desertification reversion area in the agro-pastoral transitional zone of Ningxia, as our study area. Human activities in this region have clearly interfered with natural processes, and the expansion and reversal of desertification present sharp contrasts. We constructed an evaluation index system to assess the vulnerability of the desertification reversion process. This system includes four levels, five groups, and forty-one concrete indicators, encompassing a moisture index, ecological governance index, and sandy land proportion. Finally, we explore the logical causality between the five elements of drivers, pressure, status, impact, and response, while discussing quantitative calculation methods for vulnerability, aiming to scientifically evaluate the vulnerability of the desertification reversion process and provide a scientific basis for further governance and regulation of desertification in this type of region.

Keywords: desertification reversion; vulnerability; socio-ecological systems; DPSIR framework; evaluation index system; Yanchi County

1. Conceptual Definition of Desertification Reversion Process Vulnerability

Desertification is a land degradation process marked primarily by wind-sand activity, essentially resulting from internal incoordination within socio-ecological systems [1]. As the reverse transformation of desertification, desertification reversion represents the vision of desertification control. In the agro-pastoral transitional zone of northern China, desertified area has decreased at a rate of approximately 1,280 km² [4]. Scholars such as Zhao Halin [6] and Zhou Lihua [7] attribute this reversal to changes in land use patterns and reduced intensity of human disturbance from recent ecological protection measures, while Xun Ming et al. [8] argue that modern desertification processes are mainly constrained by climate change with minimal human impact. Wang Tao [9] and others contend that both development and reversal processes result from continuous coordination between natural ecosystems and socio-economic systems.

As social-geographic relationships and regional economic connections become increasingly close, cross-scale linkages and other factors strengthen their influence on regional socio-ecological systems. Studying desertification issues and their reversal purely from a natural ecosystem perspective does not align with modern desertification formation processes and struggles to reflect the driving mechanisms of desertification reversal. Desertification and its reversion represent typical socio-ecological system management problems that should be evaluated and regulated using socio-ecological systems theoretical frameworks. Song Yuqin et al. [10] argue that the human-land system in northern China' s agro-pastoral transitional zone is vulnerable, and that internal self-organization disorder constitutes a primary cause of severe desertification in the region.

Desertification reversion is a process from disorder to order in temporal scale and a highly ordered, absolutely non-uniform system in spatial scale [11]. Under its multiple dissipative structures, this relatively closed system with low dissipation inevitably exhibits certain vulnerability and instability—that is, the possibility of reversal trend weakening or reversing direction after negative entropy increase disturbances from various internal and external perturbations in socio-ecological systems. Key scientific questions urgently needing resolution in desertification research include: Can the desertification reversal trend be sustained? What factors slow or accelerate vulnerability? How vulnerable is the reversal process?

Building upon previous research on desertification and its reversal processes, this study takes Yanchi County in Ningxia—where human interference is evident and desertification processes present sharp contrasts—as a case study. From a socio-ecological systems perspective and using the DPSIR (Driving-Pressure-Status-Impact-Response) framework, we identify and construct a vulnerability evaluation index system for the desertification reversion process. This system identifies key influencing factors and sensitivity indicators to comprehensively reflect the process characteristics of desertification reversal in northern agro-pastoral transitional zones and the dynamic influence between socio-ecological systems. The goal is to reveal the logical relationships and causal connections among driving forces, pressure, status, impact, and response, thereby providing scientific support for systematic governance and comprehensive regulation of desertification in this region.

Desertification reversion is the recovery process after desertified land has been rehabilitated [7], representing a gradual transition of ecosystems from an unsustainable state to ecological sustainability. Macroscopically, this manifests as changes in natural ecological landscapes—vegetation growth and reduced desertification area—along with changes in lifestyles and mindsets. Microscopically, it involves increased soil moisture content, groundwater reserves, and biodiversity. Essentially, it reflects controlled human activity frequency. Currently, academic consensus on desertification definition and measurement remains incomplete, making it difficult to confirm reversal existence and evaluate reversal levels. The overlapping and ambiguous mechanisms and influencing factors of regional desertification across different times and subjects create challenges for appropriate characterization methods [14].

Most scholars use reverse data from desertification assessment indicators to judge reversal degrees [14]. Lin et al. [6] established a qualitative judgment index system for desertification forward-reverse processes based on natural factors (precipitation, groundwater depth), human factors, and vegetation indicators. Traditional ecological perspective indicators can only reflect regional changes but struggle to capture micro-sample variation degrees and processes. Using farmers —who possess dual attributes as both village-level economic actors and regional environmental perceivers—as an entry point, Wang Ya [15] et al. referenced ecological governance policy performance evaluation indicators [16] to determine desertification reversal trends through farmer cognition measurement methods and indirect manifestations such as cognition and behavioral responses.

Wang Tao [4,9], Wang Ya [15], and Wang Manman [17] argue that desertification reversal in northern China' s agro-pastoral transitional zone has been achieved through the coercive force of national policy systems, maintaining system negative entropy flow development through external energy and material supplementation to desert ecosystems via human means. Once ecological policy controls are removed, can the local vulnerable human-land system and socio-economic resources satisfy local residents' long-term and short-term economic utility maximization? Can they ensure the stability of desertification reversal phenomena and sustainability of reversal trends? Desertification reversion is a process from disorder to order in temporal sequence under multiple dissipative structures [11]. Changes in any system element trigger chain reactions in others, making the recovery process inevitably unstable and vulnerable.

Referencing domestic and international scholars' research and definitions of vulnerability from a socio-ecological systems perspective, combined with desertification reversion process characteristics, we define desertification reversion process vulnerability as: the sensitivity of desertification reversal phenomena to various internal and external disturbances in socio-ecological systems, specifically the tendency and possibility of reversal trend weakening or reversing direction due to inability to cope with adverse disturbances.

shows vulnerability concepts across different research fields, including climate change vulnerability, cryosphere vulnerability, desertification vulnerability, ecological restoration vulnerability, groundwater vulnerability, socio-ecological system vulnerability, and water resources vulnerability.

2. Socio-Ecological Systems Theory and Analytical Framework Selection

As global change impact studies deepen and human activities intensify, environmental problem research has expanded from traditional assessments centered on single natural ecosystem resources to multi-dimensional studies of coupled ecological-economic systems incorporating economic and institutional dimensions [24]. Scholars such as Newell, Folke, and Ostrom [27] argue that singlediscipline perspectives cannot reflect these complex environmental problems and require interdisciplinary, comprehensive research. Socio-ecological systems theory provides a holistic framework for solving social and ecological problems, and studying vulnerability dynamically and comprehensively from this perspective has become an international research trend [24].

Currently, ten major frameworks exist for socio-ecological system analysis, including policy-oriented, eco-centric, vulnerability-focused, and integrated types such as DPSIR, SESF, TVUL, SLA, ES, HES, MEFA, MTF, TNS, and ESA [28].

compares these frameworks across dimensions of object, scale, preference, orientation, and interaction type. The DPSIR framework, as a human-centered, policy-oriented framework, focuses on macro-level impacts of social systems on ecosystems. Though providing a comprehensive diagnostic framework, its internal variable settings lack causal and logical connections, making it less suitable for vulnerability analysis. Eco-centric frameworks like ES, MEFA, TNS, and ESA focus on ecosystem impacts on social systems but don' t match desertification reversion process characteristics. Integrated frameworks like HES and MTF struggle to reflect vulnerability formation mechanisms. Vulnerability frameworks TVUL and SLA, while reflecting internal mechanisms, emphasize ecosystem impacts on social systems, which doesn' t align with desertification reversion vulnerability definitions.

DPSIR, as a human-centered, policy-oriented framework, is most widely applied in comprehensive environmental assessments. Its basic concept is that natural factors and human economic activities drive pressures on natural resources and environment, changing environmental status and resource quality/quantity. Human society responds through environmental and economic policy adjustments to mitigate pressure and maintain system sustainability [39]. The framework fully expresses causal feedback mechanisms and information coupling relationships among factors affecting regional socio-ecological systems and desertification reversal trends, objectively answering how socio-ecological systems operate. For Yanchi County, DPSIR better reveals the causal relationships and logical connections among the five elements of desertification reversion process and its vulnerability.

1. Study Area Overview

Yanchi County is located in eastern Ningxia Hui Autonomous Region (106°30 – 107°47 E, 37°04 –38°10 N) at 1,600 m elevation, featuring two major geomorphic units: loess hills and Ordos gentle slopes. With a mid-temperate continental climate, it lies east of Helan and Liupan Mountains, borders the Mu Us Sandy Land to the north, and adjoins the Loess Plateau to the south, serving as an important ecological protection barrier in the middle Yellow River region. Grassland accounts for 81.08% of its 13,68.70 km² area, making it a pastoral-predominant agro-pastoral transitional zone that was once among northwest

China' s most severely desertification-affected regions [40]. Following national ecological protection policies implemented in 2000, desertified area decreased from 3,509.80 km² to 494.40 km², with the proportion dropping from 64.25% to 10.18%, demonstrating sharp contrasts between desertification expansion and reversal.

2. Construction of the Evaluation Index System

The index system forms the foundation for evaluating desertification reversion process vulnerability. The representativeness of selected indicators, data availability, and proper embedding within the analytical framework directly affect evaluation accuracy. Using the desertification reversion process vulnerability index of Yanchi County as the target layer, we selected natural and socio-economic categories as criterion layers to fully reflect the comprehensive desertification reversion process and reveal potential causal chains from driving forces through pressure and status to impact and response measures. Based on the development process characteristics and environmental element types of criterion layers, we stratified element layers and established corresponding evaluation indicators.

Following principles of completeness, scientific rigor, and operability, combined with data availability, desertification reversion vulnerability definitions, and domestic/international desertification evaluation index systems [43-46] and desertification reversal judgment indicators [6,14], we constructed a desertification reversion process vulnerability evaluation index system aligned with Yanchi County' s socio-ecological system development characteristics and causal relationship chains, incorporating expert consultation opinions.

2.1 Driving Force Indicators Analysis

Driving forces represent the fundamental power and potential causes triggering regional ecological environmental changes, including natural and social drivers. Research shows that during 1981-2006, natural factors contributed up to 32.4% to land desertification [41], primarily through precipitation and evaporation. Yanchi County, located in the arid/semi-arid transition zone from the Ordos platform to the Loess Plateau with a mid-temperate continental climate, receives 296-355 mm average annual precipitation—less than 1/6 of evaporation. The moisture index, as a crucial climate change metric, drives desertification forward-reverse processes.

Human activities alter natural process nature and intensity within certain ranges and degrees [47]. Since 2001, when Yanchi County became a pilot county for the Grain-for-Green Program and implemented comprehensive grassland grazing bans in late 2002, grassland resources recovered significantly. These policies forced farmers to adjust traditional livestock and planting structures, changing production material flows and labor resource allocation, with remarkable desertification reversal effects: desertified area decreased from 3,509.80 km² to 494.40 km², and proportion dropped from 64.25% to 10.18%.

As the grazing ban policy was implemented county-wide, indicators of ban area proportion and intensity became meaningless. Therefore, we selected the ecological governance index (proportion of grain-for-green area to regional territory) to characterize policy driving effects, while grazing ban effects were reflected through indirect impacts on farmer production behavior and regional industrial development. Human activity intensity relates closely to resource users' livelihood patterns and adaptation strategies. In Yanchi County, where 81.08% of the 139,100 population are farmers, these micro-level economic actors serve as key links between ecological policies and environmental outcomes.

presents the driving force indicators for desertification reversion vulnerability assessment in Yanchi County, including climate moisture index (ratio of annual precipitation to evaporation), ecological governance index, and population urbanization rate.

2.2 Pressure Indicators Analysis

Pressure, indirectly caused by human activities, represents explicit manifestations of driving forces' implicit effects and constitutes direct causes imposing on socio-ecological systems and triggering status changes. Pressures generally include bearing pressure, development pressure, and resource pressure.

Bearing pressure refers to how biological individual numbers affect ecosystem regulation and carrying capacity under specific environmental conditions. As a typical agro-pastoral production zone, Yanchi' s socio-ecological system centers on humans as primary actors and livestock as key active agents. We selected population density, natural population growth rate, and livestock density to reflect ecological bearing pressure.

Socio-economic driving forces intensify human activity scope and magnitude, particularly through county government GDP targets, fixed asset investments, and spatial urban expansion, creating enormous development pressure on regional ecological environments. Resource pressure originates from resource consumption intensity and utilization efficiency. Yanchi County, with scarce water resources (no major rivers, 0.269 billion m^3 average annual surface water, and 0.620 billion m^3 groundwater), relies primarily on precipitation that varies significantly in monthly distribution and spatial patterns. To address drinking water and industrial/agricultural needs, extensive mechanical wells were excavated. We selected mechanical well numbers and water consumption to characterize water resource development pressure and utilization efficiency.

details pressure indicators including population density, natural growth rate, livestock density, GDP targets, fixed asset investment per unit area, urban spatial expansion, per capita ecological footprint, and enterprise water consumption per GDP unit.

2.3 State Indicators Analysis

Status represents the direct reflection and current manifestation of regional ecological environment in climate, soil, and landscape aspects, showing measurable ecological characteristics or trend changes caused by combined driving forces and pressures. Yanchi County’ s two geomorphic units—loess hills and Ordos gentle slopes—form the realistic foundation for desertification drivers. Long-term cultivation, five large flowing sand belts, and unreasonable farming/overgrazing have made desert the primary landscape in Ordos gentle slope areas, creating fragile ecological conditions.

We selected natural indicators (wind days, extreme high temperature days, surface runoff), ecological indicators (grassland coverage, average grass height, soil moisture content, soil organic matter, species diversity), and desertification judgment indicators (sand land proportion) to reflect the ecological state of desertification reversion processes. Groundwater depth, reserves, and quality are crucial water resource metrics and key factors affecting flora and fauna growth. However, in ecologically transitional areas like Yanchi with heterogeneous landscapes, groundwater unit representativeness is unclear, so these were excluded.

presents state indicators including local windy days, extreme high temperature days, surface runoff, grassland coverage, grass height, soil moisture content, soil organic matter, species diversity, and sand land proportion.

2.4 Impact Indicators Analysis

Impact measures how environmental status changes, under pressure and driving forces, affect social development, economic levels, and people’ s livelihoods. Socio-economic driving forces and ecological pressures alter economic structure, industrial proportions, agricultural population livelihood patterns, urban employment opportunities, unemployment rates, farmer income channels, and income gaps between urban and rural residents.

Grazing bans changed traditional production modes in resource and labor allocation, creating new economic opportunity chains. The adaptation process formed a pathway: livelihood strategy non-agriculturalization → livelihood diversification → increased farmer income → urban employment orientation → population migration to towns → reduced natural resource demand/intensity → desertification reversion → decreased agricultural population → reduced grassland ecosystem pressure.

Desertification reversion and grassland ecosystem improvement enhanced land productivity, primarily manifested as increased fresh grass yield per hectare and cultivated land grain productivity. Since coordinated agricultural-pastoral development is key in transitional zones [48], improving grain productivity per hectare allows, under local food self-sufficiency conditions, conversion of remaining farmland to forage crops, effectively regulating the supply-demand balance between livestock grass requirements and grass yield.

shows impact indicators including secondary/tertiary industry proportions, non-agricultural livelihood population proportion, urban registered unemployment rate, urban-rural income ratio, rural household per capita net income, grassland productivity, and cultivated land grain productivity.

2.5 Response Indicators Analysis

Responses are positive measures and feedback adjustments adopted by humans to adapt to and prevent environmental changes, reduce pressure and impact between socio-economic and ecological systems, and enhance natural and humanistic driving forces for desertification reversion. These include socio-economic coping mechanisms and ecological environmental protection measures.

Socio-economic responses can be reflected through: crop planting proportion for livestock feeding (micro-level land use change), animal husbandry output value proportion and sheep growth trends (macro-level industrial development changes), and education investment (teacher-student ratios, fiscal expenditure proportion), which promotes socio-ecological system resilience [49] and drives rural-urban migration.

Ecological protection responses in Yanchi manifest in ecological protection and pollution control. As a vulnerable agro-pastoral transitional zone, desertification and soil erosion are critical issues. Environmental investment represents important protection measures. Since water pollution poses the greatest ecological threat (Yanchi' s sandy loess parent material has large pores that easily contaminate groundwater), we selected industrial wastewater treatment proportion to total discharge to reflect pollution control intensity.

presents response indicators including crop planting proportion for livestock, animal husbandry output proportion, sheep growth rate, education expenditure proportion, teacher-student ratio, ecological construction investment proportion, and industrial wastewater treatment proportion.

4. Discussion

4.1 Logical Causality Exploration of the Five DPSIR Elements

The DPSIR framework, as a human-centered, policy-oriented conceptual model based on causal relationships [39], encompasses socio-ecological system dimensions from climate elements and socio-economic development drivers through resource and management structural elements. It describes how human activities create environmental and resource consumption pressures, manifesting in ecosystem status changes that feedback to social systems' industrial structure, economic opportunities, and production modes, potentially forming new adaptive cycles. This interactive chain clarifies how human activity-induced environmental changes affect social systems and why corresponding countermeasures are needed to promote sustainable socio-ecological development.

[Figure 1: see original paper] illustrates the logical relationship diagram of desertification reversion process vulnerability based on the DPSIR framework.

4.2 Quantitative Calculation of Desertification Reversion Vulnerability Based on DPSIR

Vulnerability assessment is crucial for reflecting system risk sensitivity and coping capacity, providing direction for vulnerability regulation [24]. Common methods include comprehensive index method, principal component analysis, function model method, and spatial overlay analysis [19,23]. While differing in understanding vulnerability components and disturbance types, all approaches treat vulnerability as a function of system exposure, sensitivity, and adaptive capacity.

Exposure represents inherent system states and characteristics. Sensitivity reflects system responsiveness to internal/external stimuli [13]. Adaptability, the core actors' capacity to take beneficial measures, determines vulnerability intensity. Some scholars [50-51] treat adaptability as a factor to be subtracted, while most [53] view vulnerability as the quotient of system state sensitivity and coping capacity.

Desertification is a typical socio-ecological system management problem. The DPSIR-based vulnerability relationship can be expressed as: Vulnerability = (Driving Pressure × Social-Ecological System Sensitivity) / Adaptive Capacity of Core Actors. This includes driving factors promoting reversal, pressures and status manifestations experienced by natural ecosystems, and response measures.

4.3 Research Limitations and Prospects

This DPSIR-based evaluation system reflects desertification reversion process characteristics and vulnerability relationships, with quantifiable indicators and operational feasibility, but has limitations: (1) The design primarily adopts temporal and actor perspectives, with insufficient consideration of spatial differentiation; (2) Human factors like public environmental perception and policy institutions are mostly qualitative, difficult to quantify due to sample size and data accumulation limitations; (3) The index system is based on closed-space, independent systems, while adjacent regional changes or market fluctuations create cross-scale disturbances; (4) Current indicators show high correlation, with insufficient examination of subjective factors.

Future research should emphasize cross-scale influences, apply principal component analysis to reduce indicator correlation, and conduct applicability tests during empirical analysis to simplify and optimize the evaluation system. The DPSIR framework provides a basic conceptual model for comprehensively analyzing desertification reversion processes and their driving mechanisms. This Yanchi County case study constructs a vulnerability evaluation index system covering climate moisture index, ecological governance index, and sand land proportion, with scientific rigor and quantifiability. It can indicate natural and human activity impacts on desertification reversal and human response measures, with potential practical value and policy guidance significance for application to other desertification regions.

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