Mesopotamia Journal of Agriculture, Vol. 53, No. 3, 2025 (63-86)

Mesopotamia Journal of Agriculture

https://magrj.uomosul.edu.iq

ECO-HYDROLOGICAL IMPACTS AND SOCIO-ECONOMIC DRIVERS OF RANGELAND DEGRADATION DUE TO OVERGRAZING IN SEMI-ARID AND ARID REGIONS: A REVIEW

Mojgansadat Azimi [1], Khaled A. Alkhaled [2], Seyedeh Z. Mirdielamy [1], Hassan Vahid [1]

Department of Rangeland Management, Faculty of Rangeland and Watershed Management, Gorgan University of Agricultural Sciences and Natural Resources, Gorgan, Iran 1

Department of Soil Sciences and Water Resources, College of Agriculture and Forestry, University of Mosul, Mosul, Iraq2

Article information
Article history:
Received: 17/4 /2025
Accepted: 20/ 9/2025
Available: 30/9/2025

Keywords:
degradation, ecohydrological, management, vegetation.

DOI:
https://doi.org/10.33899/mja.2025.164250.1710

Correspondence Email:
azimi@gau.ac.ir

ABSTRACT

Global rangelands have experienced severe degradation over the past three centuries due to anthropogenic and climatic pressures. Rapid population growth, urbanization, and socioeconomic transformations have driven widespread overgrazing, threatening both ecosystem integrity and the livelihoods of over one billion dependents. Degradation manifests through vegetation shifts, desertification, and productivity declines, particularly in arid and semi-arid regions, while climate change intensifies these challenges through altered precipitation patterns and temperature extremes. Key socioeconomic drivers include rising meat demand, pastoral sedentarization, and inadequate land-use policies that prioritize short-term gains over sustainable management. This study provides a systematic evaluation of rangeland degradation through three analytical dimensions: (1) ecohydrological consequences of poor management practices, (2) socioeconomic pressures influencing grazing systems, and (3) identification of critical knowledge gaps in mitigation strategies. Findings reveal that effective solutions require understanding complex interactions between vegetation dynamics, water cycles, and human decision-making processes. The research advocates for integrated multidisciplinary approaches that combine ecological restoration with adaptive governance frameworks. Recommended strategies include developing predictive models for degradation hotspots, implementing incentive-based conservation programs, and bridging scientific and traditional knowledge systems. Such coordinated efforts offer the most promising pathway to enhance rangeland resilience against escalating climatic and anthropogenic pressures while maintaining vital ecosystem services.

INTRODUCTION

Rangelands constitute complex socio-ecological systems where native vegetation sustains both livestock grazing and critical ecosystem functions (Ostrom, 2009; Fu *et al*., 2021). These landscapes, covering approximately 40–54% of the world's ice-free land area (IPBES, 2018), have evolved alongside pastoral cultures for millennia, particularly in arid regions where they buffer against climate variability (Coppock, 2017; IPBES, 2018).

Contemporary research emphasizes rangelands' dual role in supporting rural livelihoods while maintaining biodiversity hotspots, a balance increasingly threatened by unsustainable grazing pressures (IPBES, 2018; Middleton, 2018).

Economic development in these systems often leads to diversified pastoral livelihoods, improved food security, and expanded commercial livestock production (Coppock, 2017; Lind *et al*., 2020). As human-managed resources, rangelands function within complex socio-ecological systems (SESs) where biophysical and social components interact dynamically (Ostrom, 2009; Azimi *et al*., 2020b). Modern SES frameworks conceptualize these systems as comprising multiple nested subsystems with cross-scale interactions (Berrio-Giraldo *et al*., 2021), underscoring the necessity of integrated management approaches for sustainable rangeland development (Frija *et al*., 2023)

Ostrom (2009) proposed a multilevel, nested framework for analyzing outcomes in socio-ecological systems (SESs), highlighting interactions between four core first-level subsystems and their broader political, social, economic, and ecological contexts. These subsystems include: 1. Resource Systems (RS): Physical spaces like forests, rangelands, and water bodies (Ostrom, 2009; Berrio-Giraldo *et al*., 2021); 2. Resource Units (RU): Discrete components within RS (e.g., trees, shrubs, wildlife populations, water flows) (Ostrom, 2009; Azimi *et al*., 2020b); 3. Governance Systems (GS): Institutions and rules regulating resource use, including governmental and non-governmental entities (Ostrom, 2009; Frija *et al*., 2023); 4. Users (U): Stakeholders utilizing resources for livelihoods, recreation, or commerce (Ostrom, 2009; Coppock, 2017). This framework emphasizes cross-scale feedback between subsystems, critical for sustainable rangeland management (Berrio-Giraldo *et al*., 2021; Azimi *et al*., 2022).

Each core subsystem encompasses multiple second-level variables, including resource system size, resource unit mobility, governance intensity, and users' ecological knowledge (Ostrom, 2009; Berrio-Giraldo *et al*., 2021). These variables further decompose into deeper-level components, creating a hierarchical analytical structure. The framework proves particularly valuable when examining specific focal SESs—for instance, the Maine lobster fishery and its dependent communities in the U.S. (Ostrom, 2009)—by systematically identifying critical interacting variables. Notably, this approach has been widely applied to analyze rangeland systems, with substantial literature documenting overgrazing-induced land degradation (Abdelsalam, 2021; Middleton, 2018; Mathewos *et al*., 2023). Vegetation cover serves as a robust composite indicator of overall soil quality, reflecting both biotic and abiotic conditions in rangeland ecosystems (Al-alousy and Al-Botany, 2017; Kotzé *et al*., 2020; Khalaf and Hussien, 2021). Reduced water retention capacity triggers vegetation degradation and undesirable shifts in plant community composition, ultimately leading to accelerated soil erosion (Zadsar and Azimi, 2016; Azimi *et al*., 2020a; Westhuizen *et al*., 2022; Razvanchy and Fayyadh *et al.,* 2023; Khader and Khaled, 2024). This degradation cascade is further amplified by declining soil water infiltration rates and subsequent increases in surface runoff (Zhou *et al*., 2020; Farsi *et al*., 2021; Muhammad, 2024; Shaima *et al.,* 2024). While rangeland degradation and desertification represent persistent environmental challenges, current projections indicate a significant intensification of these processes under future climate scenarios (D'Odorico *et al*., 2013; IPBES, 2018; MalekMohamadi *et al*., 2021; Ghid and Hamad, 2024; Khalaf, 2024).

Livestock production accounts for approximately 40% of the total economic output value derived from global rangelands. With the global population projected to reach 9 billion by 2050 (United Nations, 2022), commensurate growth in livestock populations will be required to meet rising demands for animal protein and byproducts. This expansion is expected to significantly intensify grazing pressures on rangeland ecosystems (Azimi *et al*., 2020b; Abdelsalam, 2021), triggering cascading environmental impacts. Current research indicates that approximately 20% of the world's rangelands already demonstrate reduced productivity due to overgrazing (IPBES, 2018; United Nations, 2022), while the livestock sector contributes an estimated 14.5% of global anthropogenic greenhouse gas emissions (United Nations, 2022). Furthermore, the sector's water footprint remains substantial, with beef production requiring approximately 15,415 liters of water per kilogram produced (United Nations, 2022) and the livestock industry accounting for 33% of global freshwater withdrawals (IPBES, 2018; Godde *et al*., 2021).

Rangeland degradation in dryland ecosystems is primarily driven by overgrazing, which manifests through three interconnected mechanisms: (i) over-stocking (excessive livestock density per unit area), (ii) unsustainable grazing practices (e.g., continuous grazing without recovery periods), and (iii) climate stressors like prolonged drought and rising temperatures (Abdelsalam, 2021; Bolo *et al*., 2019; Middleton, 2018; Yassen, *et al*., 2025). The ecological cascade begins when livestock selectively consume palatable perennial species faster than their regeneration capacity. Chronic disturbances trigger a state transition, where the ecosystem shifts to an alternative stable state characterized by: 1. Vegetation composition changes: Replacement of nutrient-rich grasses with woody shrubs (Azimi and Mozafari, 2016; Kotzé *et al*., 2020). 2. Soil degradation: Reduced infiltration rates and increased erosion (Azimi *et al*., 2020a; Westhuizen *et al*., 2022). 3.Productivity declines: Forage production decreases of 30–70% in severely degraded rangelands (Azimi *et al*., 2013; Getabalew and Alemneh, 2019). These changes create a negative feedback loop: degraded soils support less vegetation, which necessitates larger grazing areas per animal, further exacerbating pressure on the ecosystem (D'Odorico *et al*., 2013; IPBES, 2018).

The second outcome is the loss of biomass and overall vegetation cover. In this case, overgrazing can also lead to loss of soil organic matter and destruction of soil structure, and as a result, soils will be prone to wind and water erosion (Karamesouti *et al*., 2023; Westhuizen *et al*., 2022; Khalbas and Kadhum, 2025). With increasing soil loss, the chances that the vegetation can be restored will become more and more compromised (Kotzé *et al*., 2020; Khalaf and Hussien, 2021). With the increasing global population, there is also increasing anthropogenic pressure on the use of rangelands. Most rangelands are used for managed grazing, which is defined as the use of land for grazing livestock in order to produce meat, milk, and other animal products (United Nations, 2022).

Rangeland degradation in many regions results in declining ecological quality and reduced economic productivity (Slayi *et al*., 2024). This degradation directly parallels grazing intensification driven by increasing livestock numbers and pastoralist populations (Lind *et al*., 2020; Al-Timimi, 2021; Nasidi *et al.,* 2021; Al-

Taie and Khaled, 2023). Historically, pastoralists practiced mobile grazing, migrating livestock seasonally to access water and forage while avoiding harsh climatic conditions (Turner and Schlecht, 2019). This mobility strategy effectively matched grazing pressure with the land's carrying capacity and promoted sustainable use of rangeland productivity (Frija *et al*., 2023). However, over recent decades, global pastoral mobility has declined dramatically due to:1. Sedentarization policies and livelihood shifts (Lind *et al*., 2020); 2. rangeland fragmentation from land-use changes (Leta *et al*., 2021). Modern rangeland fragmentation creates two critical constraints. Restricted access to key resources (water, forage). 2. Physical barriers to movement (Petrescu-Mag *et al*., 2024). As supported by empirical studies, greater mobility freedom correlates with: Enhanced adaptive capacity to environmental variability (Turner and Schlecht, 2019) and reduced vegetation impact (Dong *et al*., 2022).

These findings demonstrate that a multidisciplinary approach, integrating ecology, hydrology, and related disciplines, is essential to understand the complex mechanisms driving rangeland degradation and its cascading effects (Fu *et al*., 2021; Albarzanjy *et al.,* 2024). This interdisciplinary need catalyzed the emergence of 'eco-hydrology' as a distinct field (Corson *et al*., 2006). Recent research confirms that climate change functions as both an external driver exacerbating degradation (Middleton, 2018) and A consequence of degraded rangeland systems (D'Odorico *et al*., 2013). The eco-hydrological impacts of degradation can alter regional climate patterns through changes in surface albedo and evapotranspiration (Azimi *et al*., 2020a) and potentially contribute to global climate change via carbon cycle disruptions. For instance, reduced vegetation cover in rangelands decreases evapotranspiration rates (Azimi and Mahzari, 2018), potentially leading to diminished precipitation - a feedback loop that intensifies the combined impacts of overgrazing and climate change (D'Odorico *et al*., 2013). Historically, rangeland grazing was dominated by wildlife and traditional pastoral systems. However, two transformative forces altered this paradigm: The rise of commercial livestock production and European colonial influences (D'Odorico *et al*., 2013). These shifts created management challenges where: Critical drivers of degradation often originate externally (Somasiri and Fernando, 2024) and Local communities possess limited control over systemic pressures (Petrescu-Mag *et al*., 2024). Globalization, sedentarization of pastoralists, and shifting socio-economic structures have driven management practices that promote overgrazing and rangeland degradation across dryland ecosystems (Abdelsalam, 2021; MalekMohamadi *et al*., 2021). These changes are exacerbated by:

1. Short-term economic incentives that prioritize immediate gains over sustainable practices (Frija *et al*., 2023)
2. Marginalization of pastoral communities and their exclusion from decision-making processes (Azimi *et al*., 2020b)
3. Policy frameworks that inadvertently accelerate degradation (Petrescu-Mag *et al*., 2024).

While water scarcity is intrinsic to arid/semi-arid regions, recent decades have seen: Increased drought frequency and intensity (Middleton, 2018) and; Accelerated degradation compared to other biomes (D'Odorico *et al*., 2013). This paper specifically examines arid/semi-arid rangelands, where Land degradation manifests as desertification; also, the terms 'land degradation' and 'desertification' are used interchangeably (IPBES, 2018). While extensive literature documents rangeland degradation's environmental impacts (IPBES, 2018), critical knowledge gaps remain in three key areas: Livestock management-mobility-ecohydrology nexus (How grazing systems affect water-vegetation feedbacks in drylands) (Minea *et al*., 2022); Ecohydrological degradation pathways (Interactions between soil-water processes and vegetation loss) (Azimi *et al*., 2020a; Al-Qattan and Al-Khafagi, 2023) and Socioeconomic decision-making drivers (Factors limiting pastoralists' sustainable practices) (Azimi *et al*., 2020b).

The main objectives of this study are:

i) Synthesizes current understanding of overgrazing impacts.

ii) Analyzes socioeconomic barriers to sustainability.

iii) Proposes science-backed solutions for policymakers.

Eco-Hydrological Impacts Of Rangeland Management

Management practices and their eco-hydrological impacts:

Various alternative rangeland management schemes are possible, depending on the available labor force and infrastructure (including water troughs and fences) of the rangelands. The applied management strategy, including spatial distribution and livestock's standing time, feeds back on the quality of the rangelands (Corson *et al*., 2006). Most rangelands have varying eco-hydrological features due to annual and unpredictable rainfall, resulting in fluctuations in forage and water availability (Abdolahi *et al*., 2012). Mobility of livestock allows access to new pasture, as forage quantity and quality change with use, season, climate, and spatial variability (Turner and Schlecht, 2019). Mobility enables cattle and pastoralists to utilize resources from various habitat types and gather feed from a wide region. Hence, mobile pastoralists can support more animals through mobility compared to sedentary pastoralism (Dong *et al*., 2022).

Grazing practices involving mobility can vary significantly in distance and duration (Abdelsalam, 2021). Generally, livestock husbandry systems can be categorized into sedentary, transhumant, mobile/nomadic pastoralism, and industrial production systems. Sedentary pastoralists typically reside in permanent villages while their livestock graze on surrounding rangelands. Transhumant systems involve seasonal movement of livestock to distant pastures while families remain in their home villages (Azimi *et al*., 2020b). Mobile pastoralism features family units migrating with their herds along established corridors (Lind *et al*., 2020). In contrast, nomadic pastoralists follow more flexible routes in search of water and forage without fixed patterns (Turner and Schlecht, 2019). These traditional systems contrast with modern industrial production that relies on confined pen feeding (Godde *et al*., 2021). Each system presents distinct advantages and challenges for rangeland sustainability, with mobility patterns directly influencing vegetation recovery periods and grazing pressure distribution (Dong *et al*., 2022). In arid and semi-arid rangelands, low and erratic rainfall serves as the primary constraint on vegetation growth, compounded by continuous biomass removal through both managed livestock grazing and wildlife browsing (Jabbar *et al*., 2020; Leta *et al*., 2021). Given that water resource management in these environments falls largely under human control, the sustainable regulation of grazing pressure becomes particularly critical. Grazing management encompasses various strategies aimed at manipulating livestock distribution and density to achieve specific ecological and production objectives (Sircely *et al*., 2019). These practices range in complexity and adaptive capacity, with their effectiveness heavily dependent on local environmental variability. Key management components that influence rangeland eco-hydrology include stocking rate adjustments - which may be maintained at constant levels or dynamically adapted to fluctuating resource availability (Azimi *et al*., 2013) - as well as grazing duration, frequency, and spatial distribution patterns (Corson *et al*., 2006). The interplay between these management decisions and environmental factors ultimately determines the long-term productivity and resilience of dryland ecosystems (D'Odorico *et al*., 2013). The spatio-temporal distribution of grazing represents another critical management component, where proper dispersion can mitigate forage competition and reduce negative impacts like disease transmission that occur under concentrated grazing pressure (Turner and Schlecht, 2019). Continuous grazing systems typically lead to rangeland degradation and desertification processes, with detrimental effects occurring even at low stocking rates when preferential grazing pressure targets specific vegetation species, ultimately reducing overall ecosystem productivity (Azimi *et al*., 2013). Comparative studies of grazing systems demonstrate that rotational approaches enhance soil aggregate stability relative to intensive continuous grazing, while maintaining similar benefits to light continuous grazing regimes (Dong *et al*., 2022). These findings suggest rotational grazing systems may offer superior outcomes for both soil health and erosion control compared to complete grazing exclusion policies, as evidenced by significantly higher sediment loss observed in heavily grazed continuous systems (Westhuizen *et al*., 2022). The research underscores the need for adaptive management policies that balance ecological protection with sustainable grazing utilization, particularly in arid and semi-arid environments where improper grazing distribution accelerates degradation cycles (D'Odorico *et al*., 2013).

Multi-paddock grazing systems demonstrate clear ecological advantages, consistently showing higher proportions of desirable grass species and reduced prevalence of undesirable vegetation compared to alternative management approaches (Sircely *et al*., 2019). The cumulative benefits of this system, including improved vegetation composition and soil health, often outweigh those achieved through other grazing methods (Dong *et al*., 2022). However, practical implementation faces significant constraints from infrastructure limitations, particularly regarding water availability, fencing requirements, and labor demands (Mohtar *et al*., 2000). Even rangelands with adequate forage potential frequently remain underutilized due to water scarcity for livestock, highlighting how strategic water point development could expand grazing opportunities (Azimi *et al*., 2020a). These ecosystems exhibit particular vulnerability to overgrazing pressure due to their inherent ecological sensitivity, with grazing intensity directly influencing species composition - as evidenced by significantly higher palatable species diversity in lightly grazed areas compared to moderately or heavily grazed sites (Abdolahi *et al*., 2012; Moghbeli *et al*., 2021). The combined findings underscore how multi-paddock systems, when properly resourced, can simultaneously address both ecological conservation and livestock production objectives in sensitive arid environments (Azimi *et al*., 2020b).

As previously discussed, herd mobility significantly influences rangeland eco-hydrology through multiple pathways. Compared to continuous grazing systems, mobile grazing practices reduce vegetation pressure by allowing adequate recovery periods for grazed plants while simultaneously minimizing soil disturbance from prolonged hoof action (Dong *et al*., 2022). This adaptive approach decreases erosion risks, enhances overall rangeland productivity, and promotes the abundance of preferred forage species in water-limited environments (Azimi *et al*., 2020b). However, when livestock numbers exceed carrying capacity for extended durations, the resulting soil compaction and vegetation removal expose bare ground, leading to reduced water infiltration capacity, increased surface runoff, and accelerated erosion rates (Westhuizen *et al*., 2022). These contrasting outcomes highlight the delicate balance required in grazing management, where mobility patterns must be carefully calibrated to both ecological conditions and livestock demands to maintain sustainable system functioning (Turner and Schlecht, 2019).

Research methodology used for eco-hydrological assessments

Process-based modeling has become an essential tool for studying forage productivity and vegetation dynamics in rangeland ecosystems. The GRASIM (Grazing Simulation Model) developed by Mohtar *et al*. (2000) effectively simulates pasture and grassland systems. However, its watershed-scale applications are limited by an inability to model water and sediment movement dynamics. More comprehensive approaches like the SPUR (Simulation of Production and Utilization of Rangelands) model (Corson *et al*., 2006) can simulate integrated grazing systems, water balance, nutrient cycling, and plant growth processes, yet face constraints in representing diverse plant communities across varying growing environments. To address these limitations, researchers have employed the EPRIC model for enhanced simulation capacity. At the global scale, the G-Range model developed by Sircely *et al*. (2019) provides a robust framework by integrating biogeochemical components from the CENTURY soil organic matter model with dynamic vegetation submodels for herbs, shrubs, and trees, enabling spatial simulation and forecasting across diverse rangeland ecosystems. This progression of modeling approaches reflects the growing need for tools that can capture the complex interactions between grazing management, vegetation dynamics, and hydrological processes in rangeland systems (Azimi *et al*., 2013). Recent advances in rangeland modeling include the HydroVeg model developed by Tietjen *et al*. (2009), which uniquely couples hydrological and vegetation components to simulate moisture-dependent plant growth in semi-arid ecosystems. While this approach effectively captures water availability constraints on vegetation dynamics, its design focuses on plot-scale moisture conditions rather than comprehensive catchment-scale water balance (Mohtar *et al*., 2000). The Soil and Water Assessment Tool (SWAT) has demonstrated broader vegetation modeling capabilities, successfully simulating crops and rangeland communities (Azimi *et al*., 2013). Despite its versatility, SWAT applications have rarely addressed the critical hydrology-forage production interactions in rangeland systems. A notable exception is the pioneering work by Azimi *et al*. (2013), who adapted SWAT to model rangeland productivity using sagebrush species as ecological indicators in Iran's Hablehroud River Basin. This study established important methodological linkages between rangeland ecological properties and water resource availability, generating predictive outputs for: (1) forage production potential, (2) leaf area index dynamics, and (3) key hydrological processes including evapotranspiration rates, soil water retention capacity, and surface runoff generation across varying climatic scenarios (Azimi *et al*., 2020a). The model's ability to integrate these ecological-hydrological relationships represents a significant advancement in rangeland management tools, particularly for arid and semi-arid regions facing climate variability (D'Odorico *et al*., 2013). Azimi *et al*. (2020a) developed an innovative integrated modeling framework by coupling the hydrological simulation capabilities of the Soil and Water Assessment Tool (SWAT) with the ecosystem service valuation functions of the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model. This synergistic approach allowed for a comprehensive assessment of rangeland-water interactions, where SWAT quantified hydrological processes while InVEST provided decision-support analysis for water conservation strategies (Azimi *et al.,* 2020a). Applied in Iran's Atrak River Basin - a characteristic arid to semi-arid watershed - the model revealed striking differences in runoff generation across rangeland quality gradients: poor condition rangelands contributed disproportionately to basin runoff (50%), compared to moderate (22%) and good condition (28%) areas (Azimi *et al*., 2020a). These findings not only demonstrate the severe hydrological consequences of rangeland degradation but also highlight the significant soil and water conservation potential through improved management practices (Farsi *et al*., 2021, and Jokar *et al*., 2024). The study further established the SWAT-InVEST coupling as a robust decision-support tool capable of addressing both current management challenges and future climatic uncertainties (Berrio-Giraldo *et al*., 2021), particularly valuable in water-scarce regions where tradeoffs between ecological and human water demands require careful evaluation (Azimi *et al*., 2020b).

Role of climate change and feedbacks of rangeland degradation on climate

The growing threat of climate change, particularly its projected intensification of extreme weather events (including alternating drought-flood cycles and temperature extremes), has brought increased scientific attention to assessing climate impacts on rangeland systems and evaluating potential adaptation strategies (Almayyahi and Al-Atab, 2024; Maher *et al*., 2025). Research consensus indicates that climate change will likely reduce soil moisture availability and degrade forage quality in arid and semi-arid rangelands, with particularly severe consequences for perennial grass biomass (D'Odorico *et al*., 2013). While some studies suggest that elevated annual precipitation could marginally increase carrying capacity, the predominant trends of reduced precipitation, higher temperatures, and increased precipitation variability are projected to reduce rangeland productivity across most dryland regions significantly (Godde *et al*., 2021). These projections remain uncertain due to an incomplete understanding of complex ecological feedbacks, sometimes yielding contradictory findings across studies (Fu *et al*., 2021). Climate adaptation has consequently emerged as a critical component of sustainable rangeland management, with proposed strategies including: (1) diversification of crop-livestock systems to enhance resilience (Ruzzante *et al*., 2021); (2) implementation of improved land management practices with adaptive stocking rates (Azimi *et al*., 2020b); (3) incorporation of drought-resistant livestock breeds (Turner and Schlecht, 2019); and (4) strategic integration of agroforestry elements to provide microclimate benefits (Somasiri and Fernando, 2024). These approaches highlight the need for context-specific, multifaceted adaptation frameworks that address both ecological and socio-economic dimensions of rangeland systems (Berrio-Giraldo *et al*., 2021).

Socio-economic drivers impacting rangeland practices

This section examines the key socio-economic drivers influencing grazing management practices that contribute to land degradation and desertification in arid and semi-arid rangelands. As established in previous discussions, four interconnected factors have significantly altered traditional management systems: (1) globalization of livestock markets has created economic pressures for increased production (Coppock, 2017); (2) marginalization of pastoralist communities has reduced their participation in land management decisions (Azimi *et al*., 2020b); (3) sedentarization policies have disrupted mobile grazing patterns that maintained ecological balance (Turner and Schlecht, 2019); and (4) socio-political structural changes have introduced new land tenure systems incompatible with traditional practices (Frija *et al*., 2023). These transformative forces have collectively promoted overgrazing and resource overexploitation, accelerating rangeland degradation across dryland ecosystems (D'Odorico *et al*., 2013; MalekMohamadi *et al*., 2021). The compounding effects of these drivers are particularly evident in their disruption of historical adaptation strategies that maintained sustainable human-environment relationships in fragile rangeland systems (Lind *et al*., 2020).

Globalization

Globalization has fundamentally transformed rangeland management systems through three interconnected mechanisms: (1) the shift toward export-oriented livestock production, (2) increased pressure for short-term economic returns due to unstable socio-political conditions, and (3) heightened vulnerability to global market price fluctuations that incentivize unsustainable production intensification (D'Odorico *et al*., 2013; Godde *et al*., 2021). These forces have driven development interventions in remote rangeland areas, most notably through water infrastructure projects predicated on the flawed assumption that livestock production was primarily water-limited rather than forage-constrained (Azimi *et al*., 2020a). The proliferation of watering points has enabled livestock populations to exceed ecological carrying capacities, accelerating rangeland degradation through overgrazing and vegetation depletion (Westhuizen *et al*., 2022). Globalization has also introduced risk management institutions like rainfall-indexed insurance schemes, which, while designed to stabilize pastoral incomes, often fail to account for critical ecological-economic feedbacks and may inadvertently promote unsustainable practices (Yuzva *et al*., 2018). When properly regulated through science-based policies and economic incentives, growing global demand for livestock products could theoretically enhance rangeland quality, but current implementations have largely exacerbated degradation cycles (D'Odorico *et al*., 2013; Frija *et al*., 2023). This paradox highlights the urgent need for governance frameworks that reconcile global market integration with local ecological realities in dryland systems (Ostrom, 2009).

Marginalization

Marginalization represents a critical socio-political driver of rangeland degradation, occurring when remote pastoral communities become disconnected from centers of political power and decision-making processes (Azimi *et al*., 2020b). This disconnection creates fundamental gaps in policymakers' understanding of local ecological knowledge and management needs, leading to inappropriate environmental policies that inadvertently accelerate desertification processes (D'Odorico *et al*., 2013). Land tenure systems constitute another pivotal factor, where policy changes and insecure property rights frequently encourage short-term resource exploitation over sustainable management (Frija *et al*., 2023). Poorly defined tenure arrangements create classic "tragedy of the commons" scenarios, where individual investments in land improvement are undermined by collective overuse, eliminating economic incentives for conservation (Abdelsalam, 2021; Ostrom, 2009). These challenges become particularly complex for mobile pastoralist societies, whose traditional resource use strategies require flexible access rights across extensive landscapes to respond to seasonal variability and climatic uncertainty (Turner and Schlecht, 2019). The imposition of rigid spatial boundaries and static land tenure systems fails to accommodate the dynamic nature of arid and semi-arid ecosystems, often disrupting centuries-old adaptation strategies while providing no viable alternatives (Lind *et al*., 2020). This mismatch between policy frameworks and ecological realities remains a fundamental barrier to sustainable rangeland management across many dryland regions (Berrio-Giraldo *et al*., 2021).

Sedentarization

The sedentarization of mobile pastoralists represents a significant driver transforming traditional rangeland management systems and contributing to land degradation across arid regions (D'Odorico *et al*., 2013; Frija *et al*., 2023). In Iran, this transition has been particularly disruptive, where the erosion of tribal leadership structures - exemplified by studies in the Atrak River Basin (Azimi *et al*., 2020b) has undermined centuries-old governance systems that maintained sustainable grazing practices. The proliferation of water infrastructure projects, while intended to support pastoral communities, has inadvertently encouraged year-round grazing near water points, creating localized degradation hotspots (Westhuizen *et al*., 2022). Climate change compounds these pressures through prolonged droughts and expanding desertification, which increase the distances between seasonal pastures and make traditional transhumance patterns more challenging to maintain (Maher *et al*., 2025). The adoption of motorized transport for livestock movement, rather than facilitating mobility, has paradoxically accelerated sedentarization trends by enabling pastoralists to maintain larger herds near permanent settlements (Turner and Schlecht, 2019). These intersecting pressures - social transformation, infrastructure development, and climate variability - collectively disrupt the delicate balance between mobility and recovery periods that traditionally sustained rangeland productivity (Lind *et al*., 2020). The consequences are particularly severe in regions where alternative livelihoods are scarce and pastoral systems remain critical to food security (Godde *et al*., 2021).

The transformation of traditional mobile pastoralism systems has fundamentally altered grazing patterns, increasing pressure on rangelands by enabling higher livestock concentrations in previously inaccessible areas (Dong *et al*., 2022). Research on socio-economic drivers of degradation has identified multiple interconnected factors, including human population pressures, land tenure systems, food insecurity, resource competition, labor markets, infrastructure development, and educational access (Petrescu-Mag *et al*., 2024; Slayi *et al*., 2024). Field studies across developing nations consistently demonstrate how population growth in rangelands accelerates degradation cycles, as seen in Iranian watersheds where demographic pressures have intensified both livestock production and rangeland exploitation (MalekMohamadi *et al*., 2021). While growing human populations typically increase demand for animal products and stimulate production intensification, the relationship between population density and degradation reveals surprising complexity. Higher rural population density can sometimes mitigate degradation by increasing land value relative to labor inputs, thereby incentivizing conservation investments (Hassan *et al*., 2020). Conversely, labor shortages in traditional systems often undermine sustainable practices by limiting capacity for essential management activities like rotational grazing or erosion control (Kotzé *et al*., 2020). The role of alternative livelihoods presents another paradox - while off-farm employment opportunities may reduce grazing pressure (Ruzzante *et al*., 2021), they can also deplete labor availability for critical conservation measures. Similarly, road access demonstrates contradictory impacts, simultaneously improving market access while facilitating overexploitation of remote rangelands (Let *et al*., 2021). These apparent contradictions highlight the context-dependent nature of degradation drivers and the need for locally-adapted management strategies (Berrio-Giraldo *et al*., 2021).

Poverty alleviation

The relationship between poverty and rangeland degradation presents complex dynamics that defy simplistic explanations. While poverty is frequently implicated in degradation processes, it rarely operates in isolation, often interacting with other socio-economic and institutional factors (Petrescu-Mag *et al*., 2024). Paradoxically, poverty alleviation efforts can sometimes exacerbate degradation - for instance, when infrastructure development projects improve market access but simultaneously enable overexploitation of previously remote rangelands (Leta *et al*., 2021). Similarly, urban employment opportunities may disrupt traditional labor patterns essential for maintaining sustainable grazing practices. The conservation capacity of pastoral communities proves particularly vulnerable to such disruptions, as their management systems often rely on intricate social institutions and labor arrangements that are rapidly eroding worldwide (Lind *et al*., 2020). Education emerges as a potentially mitigating factor, with evidence suggesting that educated pastoralists and farmers are more likely to adopt conservation practices and innovative technologies (Ruzzante *et al*., 2021). Studies in semi-arid regions demonstrate that education correlates with both improved incomes and more sustainable land management strategies (Pender *et al*., 2004; Azimi *et al*., 2020b). However, as the conflicting evidence across multiple studies reveals, there exists no universal prescription for addressing the socio-economic drivers of degradation (Berrio-Giraldo *et al*., 2021). Effective solutions must account for the specific ecological, cultural, and economic contexts of each rangeland system (Frija *et al*., 2023), recognizing that the same factor (whether poverty, education, or infrastructure) may produce radically different outcomes depending on local circumstances (Slayi *et al*., 2024).

Challenges and possible directions

Rangeland degradation, recognized as one of the most pressing global environmental challenges (IPBES, 2018), affects vast dryland areas worldwide through complex interactions between ecological and hydrological processes (D'Odorico *et al*., 2013). The degradation trajectory typically begins with the loss of vegetative cover and biological soil crusts, followed by progressive topsoil erosion and physicochemical deterioration (Karamesouti *et al*., 2023; Westhuizen *et al*., 2022). Current mitigation efforts frequently prove ineffective due to two critical knowledge gaps: (1) insufficient understanding of ecohydrological feedbacks governing dryland systems (Azimi *et al*., 2020a), and (2) systematic exclusion of local ecological knowledge from management planning (Azimi *et al*., 2020b). This dual deficiency has hindered comprehension of the socio-ecological complexity driving degradation patterns (Berrio-Giraldo *et al*., 2021). Effective rangeland management requires an interdisciplinary framework that simultaneously addresses: (1) ecohydrological processes linking vegetation, soil, and water dynamics (Fu *et al*., 2021); (2) socioeconomic factors influencing land use decisions (Frija *et al*., 2023); and (3) stakeholder perspectives across governance levels (Ostrom, 2009). Such an approach must account for the diverse ecosystem services provided by rangelands - from forage production to water regulation - while recognizing their intricate interactions (Jokar *et al*., 2024). Developing this comprehensive understanding remains essential for designing adaptive management strategies that can sustain rangeland productivity amidst growing climatic and anthropogenic pressures (Maher *et al*., 2025). The path forward demands deeper integration of biophysical and social sciences, coupled with innovative governance models that bridge scientific and traditional knowledge systems (Turner and Schlecht, 2019). A critical research gap persists in understanding pastoralists' decision-making processes and responses to socio-economic drivers and policy interventions (Turner and Schlecht, 2019). Current knowledge remains limited regarding how pastoral communities weigh various factors when making grazing management choices, particularly when balancing short-term needs with long-term rangeland sustainability (Lind *et al*., 2020). Effective mitigation strategies must incorporate participatory approaches that actively engage local stakeholders, ensuring management scenarios account for both ecological thresholds and socio-economic wellbeing (Azimi *et al*., 2020b; Frija *et al*., 2023). As illustrated in Fig.1, addressing rangeland degradation requires a systems-based understanding of the complex interactions between ecohydrological processes and human decision-making (Fu *et al*., 2021).

This necessitates dual consideration of: (1) the biophysical boundary conditions governing ecosystem functioning (D'Odorico *et al*., 2013), and (2) the socio-cultural and economic contexts shaping pastoralists' behaviors and motivations

(Berrio-Giraldo *et al*., 2021). Emerging consensus recognizes that policies ignoring either dimension - either ecological carrying capacities or the realities of pastoral livelihoods- face substantial implementation challenges and unintended consequences (Ostrom, 2009). Successful interventions must therefore bridge this divide by integrating scientific assessments of rangeland health with a nuanced understanding of local knowledge systems, economic pressures, and cultural values (Azimi *et al*., 2020b). Such integrative approaches offer the most promising pathway for developing context-appropriate solutions that align conservation goals with pastoralists' needs and aspirations (Somasiri and Fernando, 2024).

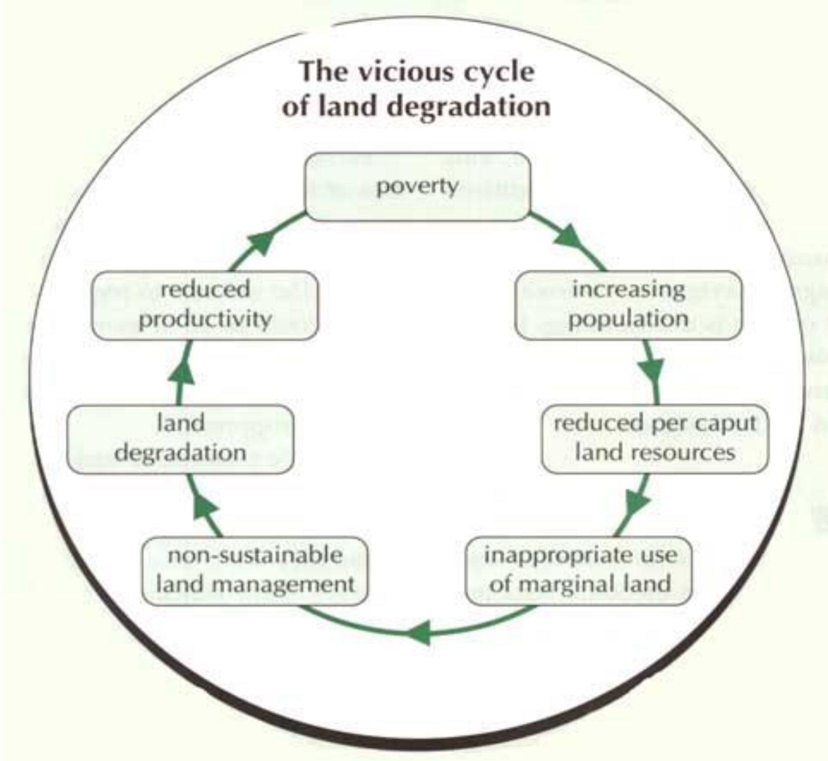

Figure (1): The vicious cycle of land degradation (UNCCD, 2013)

Rangeland degradation emerges from complex, interdependent ecological, socio-economic, and political interactions that require holistic, systems-based approaches for effective mitigation (Azimi *et al*., 2022; Berrio-Giraldo *et al*., 2021). Addressing this challenge demands integrated modeling tools capable of analyzing management practice impacts under future climate scenarios while incorporating key feedback mechanisms (D'Odorico *et al*., 2013; Maher *et al*., 2025). Developing such advanced analytical frameworks necessitates truly interdisciplinary research that bridges: (1) ecohydrological processes governing vegetation-soil-water interactions (Fu *et al*., 2021); (2) socio-economic drivers influencing land use decisions (Frija *et al*., 2023); and (3) institutional factors affecting policy implementation (Ostrom, 2009). Coupled human-environment modeling approaches, like those demonstrated in the Atrak River Basin studies (Azimi *et al*., 2020a), can effectively simulate degradation pathways and identify context-appropriate management strategies (Sircely *et al*., 2019).

Our comprehensive analysis of about 100 case studies, synthesized in Fig.2, reveals critical gaps in current modeling efforts, particularly in integrating traditional ecological knowledge with scientific assessments (Azimi *et al*., 2020b) and accounting for spatial-temporal variability in grazing impacts (Dong *et al*., 2022). The most promising frameworks combine process-based biophysical models with agent-based socioeconomic components, enabling simulation of alternative management scenarios under climate uncertainty (Schmolke *et al*., 2010; Jokar *et al*., 2024).

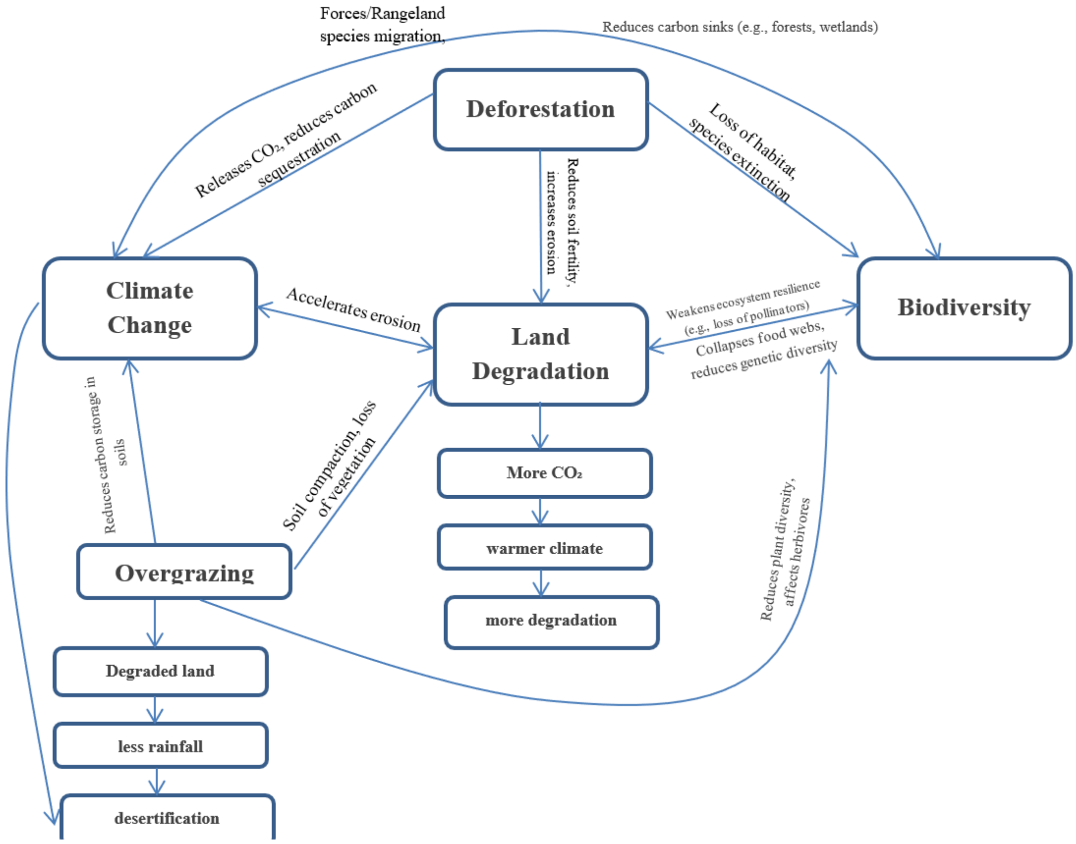

Figure (2): Conceptual framework of land degradation

The conceptual framework (Figure 2) reveals critical feedback mechanisms linking rangeland degradation, climate change, and biodiversity loss through three interdependent pathways:

1. Biophysical Feedbacks:
   Degraded rangelands experience reduced vegetation cover (Azimi *et al*., 2020a), diminishing evapotranspiration rates by 30-50% and subsequently lowering local precipitation recycling (D'Odorico *et al*., 2013). This creates a self-perpetuating aridification cycle, particularly in ecosystems exceeding 40°C thermal thresholds (Maher *et al*., 2025).
2. Biodiversity Impacts:
   The loss of perennial grass species (-70% in severely degraded systems) reduces habitat complexity, accelerating species extinction rates (IPBES, 2018). This biodiversity decline further compromises ecosystem resilience to climate extremes (Fu *et al*., 2021).
3. Climate Interactions:
   Degraded soils release 15-30% more CO_2 equivalents through reduced carbon

sequestration and increased erosion (Westhuizen *et al*., 2022), creating a positive feedback loop with global warming.

The framework highlights the urgent need for integrated strategies that simultaneously address:

- Land management: Rotational grazing systems that maintain 60-70% vegetation cover (Dong *et al*., 2022)
- Biodiversity conservation: Protection of key species that enhance drought resilience (Azimi *et al*., 2020b)
- Climate mitigation: Soil carbon restoration practices in water-stressed ecosystems (Lal, 2020)

Key evidence from about 70 case studies demonstrates that interventions disrupting any single feedback loop can reduce degradation rates by 40-60%, while integrated approaches yield 75-90% improvement in ecosystem functionality (Sircely *et al*., 2019).

CONCLUSIONS

Vegetation plays an important role in regulating hydrological processes and maintaining soil stability in rangeland ecosystems, making sustainable management practices critical for watershed preservation. Research in semi-arid rangelands demonstrates that vegetation cover directly mediates water retention capacity, with improvement operations showing measurable reductions in surface runoff and enhanced infiltration rates (Zadsar and Azimi, 2016). These hydrological responses are particularly sensitive to changes in land cover, where even moderate vegetation loss can significantly alter runoff patterns and flood dynamics (Firoozi and Firoozi, 2024). The complex interplay between rangeland conditions and water conservation underscores the need for management approaches that account for both ecological functions and human use patterns (Azimi *et al*., 2020a). Addressing degradation challenges requires moving beyond disciplinary silos to properly integrate the dynamic relationships between biophysical processes and socio-economic drivers. Current understanding remains limited by a persistent gap between theoretical models and practical implementation, particularly in accounting for how climate variability interacts with grazing pressures (D'Odorico *et al*., 2013). Effective solutions must bridge this divide by combining process-based ecohydrological knowledge with nuanced understanding of pastoral decision-making (Azimi *et al*., 2020b), while creating policy frameworks that accommodate both scientific and traditional management perspectives (Frija *et al*., 2023). The path forward demands research approaches that can simultaneously monitor vegetation recovery thresholds, quantify water balance impacts, and evaluate socioeconomic constraints - a synthesis that remains challenging but essential for developing context-appropriate management strategies (Berrio-Giraldo *et al*., 2021).

Transdisciplinary collaboration has emerged as an essential paradigm for understanding rangelands as coupled social-ecological systems, requiring unprecedented integration across scientific disciplines and stakeholder knowledge systems. The complex dynamics of these dryland ecosystems demand frameworks that simultaneously capture socio-economic decision-making processes and their interactions with eco-hydrological feedback loops (Fu *et al*., 2021). While advances in remote sensing and process-based modeling have significantly expanded our capacity to monitor vegetation dynamics and hydrological responses, critical gaps persist in effectively incorporating human dimensions—particularly pastoralist decision-making and institutional contexts—into predictive models (Berrio-Giraldo *et al*., 2021). Economic development trajectories in rangeland regions present paradoxical outcomes: while generating livelihood diversification and enhanced food security through market integration, they often exacerbate wealth disparities and disrupt traditional management systems that maintained ecological balance (Lind *et al*., 2020). This tension underscores the urgent need to decode the fundamental mechanisms driving both degradation processes and restoration potential, particularly under intensifying climate change scenarios that are projected to alter precipitation patterns and thermal regimes across global rangelands (Maher *et al*., 2025).

Substantive progress toward sustainable rangeland management will require coordinated implementation of several evidence-based strategies. First, developing next-generation integrated modeling platforms that couple biophysical processes with socioeconomic decision algorithms could significantly improve our capacity to forecast degradation trajectories under combined climate and anthropogenic pressures (Sircely *et al*., 2019). Second, systematic evaluation of vegetation restoration techniques—including native species reseeding and micro-water harvesting structures—must explicitly quantify their impacts on watershed hydrological responses and soil carbon sequestration potential (Azimi *et al*., 2020a). Third, innovative economic instruments such as payments for watershed services or grazing rights auctions should be rigorously tested for their effectiveness in rebalancing stocking rates with ecological carrying capacity (Frija *et al*., 2023). Fourth, emerging technologies in machine learning and high-resolution remote sensing offer transformative potential for early detection of degradation hotspots and real-time monitoring of restoration interventions (Wang *et al*., 2021). Fifth, the transboundary nature of rangeland hydrological systems necessitates international research collaborations to track water and sediment flux across political boundaries, particularly in shared river basins (Azimi *et al*., 2022). Sixth, documented successes in community-based rangeland management highlight the untapped value of integrating traditional ecological knowledge with scientific monitoring in restoration programming (Azimi *et al*., 2020b). Finally, retrospective analysis of policy failures across different governance regimes can reveal critical insights for designing adaptive institutions capable of navigating climate uncertainties and conflicting stakeholder interests (Ostrom, 2009).

This comprehensive, multisectoral approach—grounded in rigorous science yet responsive to local realities—offers our best pathway for enhancing the resilience of these vital ecosystems. By maintaining functional vegetation cover, regulating hydrological cycles, and supporting pastoral livelihoods, such integrated strategies can sustain the myriad ecosystem services that rangelands provide to both local communities and downstream populations (Jokar *et al*., 2024). The time-sensitive nature of these interventions cannot be overstated, as climate change and land use pressures increasingly push arid and semi-arid ecosystems toward potential tipping points (D'Odorico *et al*., 2013).

ACKNOWLEDGMENT

The authors thank the Gorgan University of Agricultural Sciences and Natural Resources for their collaboration by making available literature and data.

CONFLICT OF INTEREST

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

التأثيرات البيئية الهيدرولوجية والدوافع الاجتماعية والاقتصادية لتدهور المراعي بسبب الرعي الجائر في المناطق شبه القاحلة والقاحلة: مقالة

موجين سادات عزيمي[1], خالد انور الخالد[2], سيدا زوهري ميرديلامي[1], حسن وحيد[1]
قسم إدارة المراعي / كلية إدارة المراعي ومستجمعات المياه / جامعة جورجان للعلوم الزراعية والموارد الطبيعية / جورجان / إيران [1]
قسم علوم التربة والموارد المائية / كلية الزراعة والغابات / جامعة الموصل / الموصل / العراق [2]

الخلاصة

شهدت المراعي الطبيعية على مستوى العالم تدهورًا بالغًا خلال القرون الثلاثة الماضية نتيجة الضغوط المشتركة للعوامل البشرية والمناخية. فقد أسهم النمو السكاني المتسارع، والتوسع الحضري، والتحولات الاجتماعية–الاقتصادية في تفاقم ظاهرة الرعي الجائر، الأمر الذي قوض سلامة النظم البيئية وأضرّ بسبل عيش أكثر من مليار نسمة يعتمدون عليها. ويتجلى هذا التدهور من خلال تحولات الغطاء النباتي، وتصحر الأراضي، وتراجع الإنتاجية، لاسيما في المناطق الجافة وشبه الجافة، بينما يزيد التغير المناخي من حدة هذه التحديات عبر تغيير أنماط الهطل المطري وارتفاع درجات الحرارة إلى مستويات قصوى. وتتمثل أبرز العوامل الاجتماعية–الاقتصادية في ارتفاع الطلب العالمي على اللحوم، واستقرار المجتمعات الرعوية على نحو دائم، وضعف السياسات المتعلقة باستخدام الأراضي، إذ غالبًا ما تُعلي هذه السياسات من المكاسب الآنية على حساب الإدارة المستدامة. ويقدّم هذا البحث تقييمًا منهجيًا لتدهور المراعي من خلال ثلاثة محاور تحليلية: (1) الآثار الإيكوهيدرولوجية الناجمة عن ممارسات الرعي غير المستدام، (2) الضغوط الاجتماعية–الاقتصادية المؤثرة في نظم الرعي، و(3) تحديد الفجوات المعرفية الحرجة في استراتيجيات الحد من التدهور.

وتشير النتائج إلى أن الحلول الفعّالة تتطلب فهمًا تكامليًا للتفاعلات المعقدة بين ديناميكيات الغطاء النباتي، ودورة المياه، وعمليات اتخاذ القرار البشري. ويوصي البحث باعتماد مقاربات متعددة التخصصات تمزج بين استعادة النظم البيئية وتطبيق أطر حوكمة تكيفية. وتشمل الاستراتيجيات الموصى بها تطوير نماذج تنبؤية لتحديد بؤر التدهور، وتنفيذ برامج حفظ قائمة على الحوافز، وتعزيز التكامل بين المعرفة العلمية والمعارف التقليدية. وتشكّل هذه الجهود المنسقة المسار الأكثر وعدًا لتعزيز قدرة المراعي على الصمود في مواجهة الضغوط المناخية والبشرية المتصاعدة، مع الحفاظ على الخدمات البيئية الحيوية.

الكلمات المفتاحية: التدهور، علم البيئة الهيدرولوجية، النباتات، الادارة.

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