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Future climate change risks and sustainable pathways for pastoralism in the eastern Eurasian drylands



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Cold-season disasters (*dzud*) increasingly threaten pastoralism in the eastern Eurasian drylands, notably Mongolia, killing millions of livestock and jeopardizing the sustainability of one of the remaining significant systems of mobile pastoralism worldwide. Despite escalating climate and socioeconomic pressures, integrated prospective assessments coupling climate hazards, rangeland dynamics, and socioeconomic vulnerability remain lacking. Here we develop a climate–rangeland–society modelling framework to assess ecological and socioeconomic sustainability. The framework projects *dzud* risk through 2050 under three climatic scenarios Representative Concentration Pathways and Shared Socioeconomic Pathways (SSP1–2.6, SSP3–7.0, and SSP5–8.5) and six socioeconomic pathways—business-as-usual, SSP-aligned trends, and long-term development vision—each includes an export-enhanced variant. Across baseline pathways, *dzud* risk is projected to intensify from the mid-2030s, with annual livestock mortality reaching 8–11 million head (sheep units), driven by compounding climate hazards and increased vulnerability, particularly persistent overstocking that exceeds rangeland carrying capacity. Although hay preparedness increases modestly, persistent overstocking erodes per-animal hay availability and induces nutritional stress. By contrast, export-enhanced pathways reduce *dzud* mortality by 63–91%—preventing up to 9.5 million deaths annually—by alleviating grazing pressure while sustaining meat revenues, demonstrating that ecological and socioeconomic sustainability are mutually reinforcing. Achieving this requires coordinated investment in veterinary services, cold-chain logistics, and market governance, alongside regulatory frameworks that align herder incentives with ecological sustainability.

Drylands—defined by an aridity index below 0.65¹—support nearly two billion people and play a critical role in global food security and carbon regulation, yet they are ranked among the world's most ecologically vulnerable systems^{2–4}. Exposure to climate hazards and ecological stressors is intensifying in these regions, compounding socioeconomic vulnerabilities, particularly among marginalized communities such as pastoralists^{5–8}. Pastoralism represents a socio-ecological system in which pastoralists, livestock, and rangelands have co-evolved over millennia, sustaining biodiversity, food security, and sustainable land use^{9–11}. Despite their ecological, economic, and cultural significance, pastoralist communities remain

inadequately represented in global climate and development policy frameworks, particularly in low- and middle-income countries^{7,12–15}. The long-term sustainability of pastoralism is increasingly compromised by escalating climate hazards¹⁶, with consequent implications for progress across multiple Sustainable Development Goals¹⁷. However, integrated analyses of the interactions between climatic dynamics, rangeland condition, and socioeconomic trajectories remain limited^{15,18}.

To address this gap, we present the first integrated assessment of future climate change risks for Mongolian pastoralism in the eastern Eurasian drylands—where approximately 90% of the territory is classified as dryland

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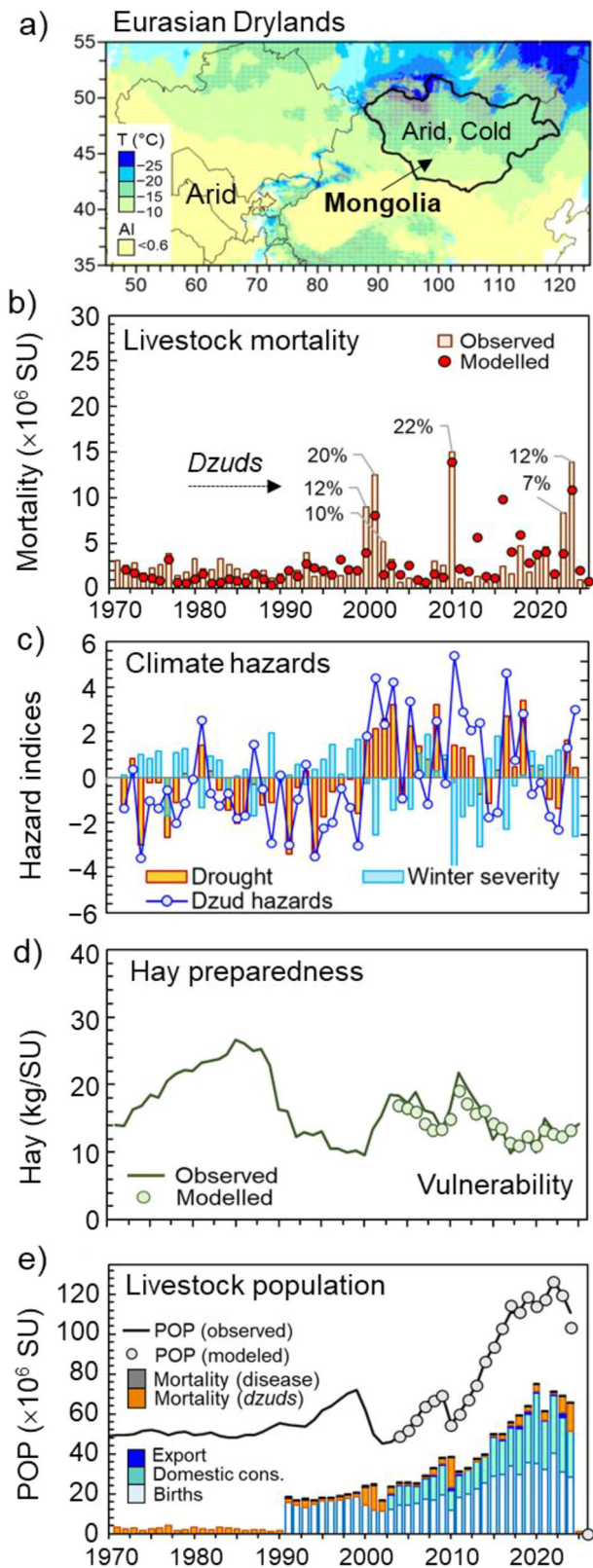


Fig. 1 | Study area and historical dzuds (livestock mortality) with controlling factors of climate hazards and herder vulnerability in Mongolia (1970–2024). **a** Mean temperature during winter (December–February, 1970–2000) overlaid on drylands (aridity index: $AI < 0.6^{112}$) across Eurasia. Mongolia reflects its unique combination of arid and cold climate; blue tones indicate temperatures below -25°C . **b** Observed and modelled mortality (sheep units: SU). **c** Climate hazards (preceding summer drought and winter severity, and their combined *dzud* index). Herder vulnerability expressed as **d** hay preparedness and **e** livestock population (POP) and its controlling factors: births (1991–2022), *dzud* mortality (1970–2024), disease mortality (1991–2020), domestic consumption (2003–2023), and exports (2003–2023). Map created using BIO11 WorldClim v2.1¹¹³ and Global-AI v3.1¹¹².

territory and support extensive livestock grazing^{19,21}, making Mongolia one of the few nations where large-scale mobile pastoralism persists as a primary livelihood system. Mongolian herders have adapted to environmental variability for centuries through mobile grazing strategies, flexible resource use, and extensive ecological knowledge embedded in cultural institutions dating to the Xiongnu and Mongol empires²². However, these historically resilient systems face mounting pressures from escalating climate risks^{23,24}, expanding desertification^{25,26}, and structural socioeconomic changes including market liberalization and land-use transformation^{27–29}. Together, these ecological and socioeconomic changes raise fundamental questions about the long-term sustainability of pastoralism in the region.

One of the most damaging climate-related risks in recent decades is the *dzud*, a cold-season disaster, driven by both climate variability and socioeconomic vulnerability^{8,28}. *Dzuds* typically occur when severe winters—characterized by extreme cold temperatures and heavy snow—follow summer droughts that deplete pastures and weaken livestock body condition, leading to mass mortality from starvation^{29,30}. The 2009–2010 *dzud*—the most severe on record—killed over 10 million animals (around 20% of the national herd), generating substantial economic losses and exacerbating rural poverty, food insecurity, and outmigration^{29,31–33}. The consecutive *dzuds* of 2023–2024 resulted in the loss of over 13 million livestock across two years³⁴. These impacts are consistently amplified by socioeconomic vulnerability factors, including livestock populations that exceed rangeland carrying capacity and inadequate hay reserves^{8,28,29}. This intersection of environmental stress and vulnerability makes Mongolia an ideal case study for pastoral sustainability risk assessment—yet integrated analyses coupling future climate and socioeconomic scenarios remain limited.

To address this gap, we develop a national-scale, scenario-based climate–rangeland–society modelling framework to assess future *dzud* risk in Mongolia through 2050. The framework integrates projected climate hazards, rangeland dynamics, socioeconomic vulnerability to evaluate ecological and socioeconomic sustainability. Ecological sustainability is defined as the maintenance of livestock populations within rangeland carrying capacity, consistent with the principle of sustainable yield—whereby extraction does not exceed ecosystem productivity^{35–38}. In this context, carrying capacity represents the threshold beyond which pasture degradation becomes irreversible. Socioeconomic sustainability is defined as the capacity of pastoral systems to sustain or improve livestock-derived revenue relative to a 2024 baseline. The most recent consecutive *dzuds* of 2023–2024 caused total economic damages of 1.5–1.9 billion USD, with 63.3% of surveyed households in the most affected regions reporting livestock losses³⁴. The framework focuses on identifying pathways that simultaneously reduce rangeland pressure, lower *dzud*-related mortality, and enhance market-oriented offtake—one of the few strategies capable of concurrently alleviating overstocking and increasing livestock-related revenue. While herders employ a range of adaptation strategies—including mobility, supplementary feeding, mixed-herd management, and social networks—nationally consistent data on these practices are not uniformly available³⁹, necessitating a macro-level modelling approach. In the Mongolian context, export-enhanced pathways should be understood not merely as increasing export volumes but as enhancing the value derived per animal and per household—ensuring that herders are rewarded for quality, timely offtake, and sustainable herd management rather than herd accumulation^{40,41}.

(aridity index below 0.65)¹, spanning desert, desert-steppe, and steppe zones¹⁹—linking climate projections, ecological conditions, and pastoral vulnerability across a range of climate and socioeconomic scenarios. Mongolia's cold and arid climate (Fig. 1a) offers a crucial perspective for examining the intersecting challenges of climate change and socioeconomic transition²⁰. Rangelands cover approximately 75–80% of the national

Climate–Rangeland–Society Modeling Framework

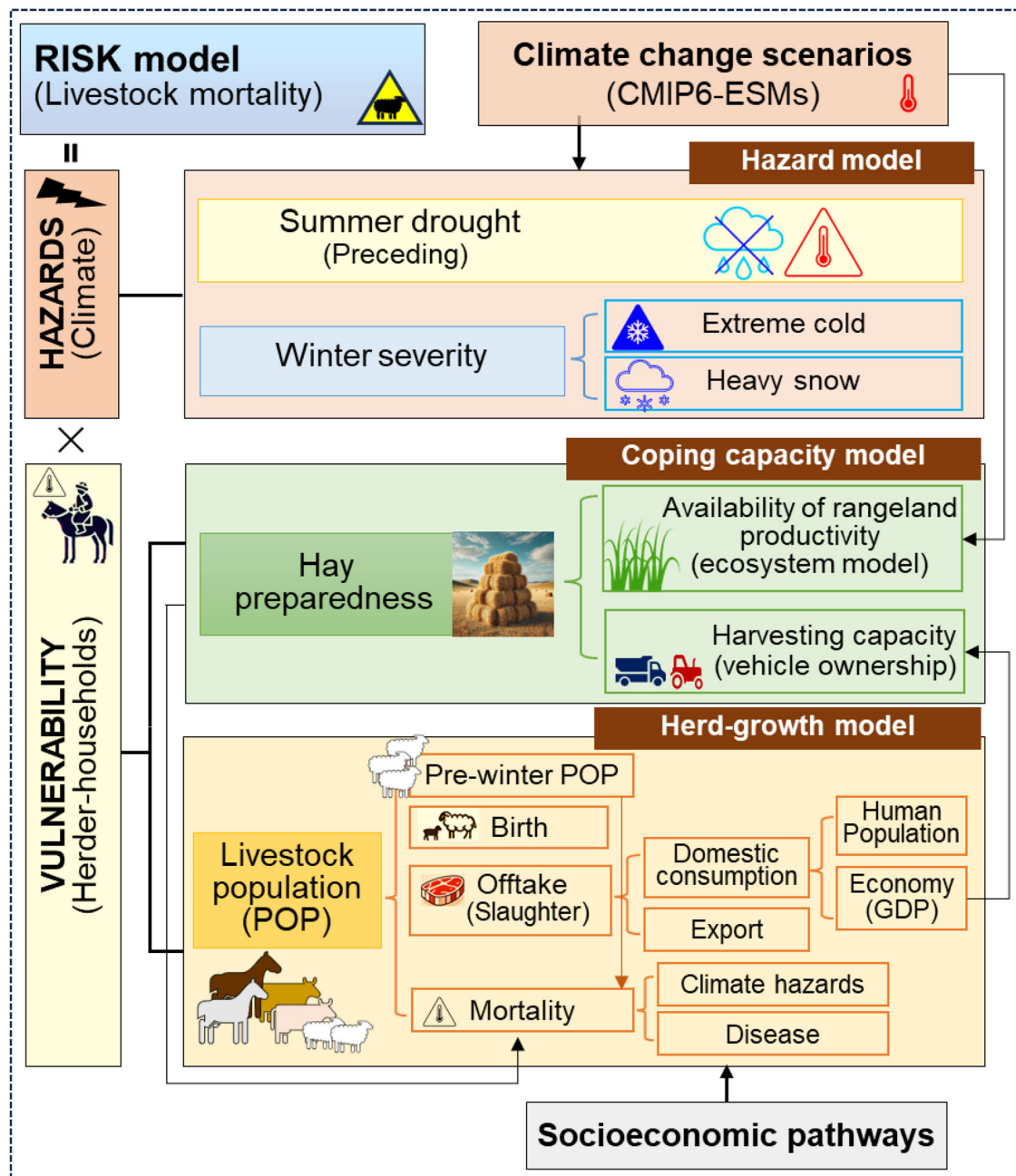


Fig. 2 | Modelling framework for dzud risk assessment under climate change scenarios and socioeconomic pathways. Dzud risk (livestock mortality) is the product of climate hazards and herder vulnerability. Hazards comprise drought and winter severity, driven by future climate projections from five ESMs from CMIP6. Vulnerability includes two components: coping capacity—hay preparedness,

estimated rangeland productivity, and household vehicle ownership—and livestock population (POP)—modelled using a herd-growth model based on the preceding POP, births, climate (dzud) mortality, disease mortality, and offtake (domestic consumption and export). Domestic consumption is modelled using income elasticity based on projected human population growth and GDP.

Here, dzud risk is conceptualised as climate-induced livestock mortality, resulting from the interaction of multiple climate hazards (hereafter multi-hazard) and herder's socioeconomic vulnerability^{8,28} (Fig. 2), consistent with the risk frameworks of the United Nations⁴² and the Intergovernmental Panel on Climate Change (IPCC)⁴³. Three global climate change scenarios—Representative Concentration Pathways and Shared Socioeconomic Pathways^{44,45} (SSP1–2.6, SSP3–7.0, and SSP5–8.5)—are integrated with six national-level socioeconomic pathways: (1) business-as-usual (PW1), representing the continuation of existing livestock management practices without substantial policy changes, (2)

national trends aligned with global SSP trajectories (PW2), and (3) long-term development vision (Vision 2050)⁴⁶ (PW3). Each pathway includes an export-enhanced variant (PW1–PW3+Export) (Table 1, Fig. 2), operating through per-animal returns rather than aggregate revenue: gradually increasing export shares raise per-animal value by prioritising quality over quantity, enabling herders to meet revenue objectives with smaller herd sizes—thereby reducing dependence on herd accumulation and alleviating grazing pressure on rangelands^{41,47}—subject to regulatory frameworks that align market incentives with ecological sustainability.

Table 1 | Socioeconomic pathway assumptions and their export-enhanced variants

Socioeconomic pathways (PW)	Vulnerability Factors		Livestock population (POP)			
	Coping capacity		Preceding POP			
	Hay preparedness		Birth	Preceding mortality		Domestic consumption
				Dzud	Disease	Export
PW1 (Business-as-Usual)	ANPP ¹ Vehicle ²	POP (herd-growth model)	POP & Mortality	Dzud model ³	10-year average ⁴	0.98% of POP (10-year average) ⁵
PW2 (National trends under SSPs)	ANPP & Vehicle (SSP-GDP) ⁷	Same as PW1				
PW3 (Vision 2050)	ANPP & Vehicle (Vision 2050 GDP) ⁷					
Export-enhanced pathways						
PW1-PW3 + Export	Same as PW1 – PW3					Logistic growth under ecologically sustainable conditions ⁹

Three pathways are considered: PW1 (Business-as-Usual – continuation of existing livestock management practices without substantial policy changes; (2) PW2 (National trends under SSPs) – GDP and human population (HPOP) trends aligned with SSP projections^{10a}; and PW3 (Vision 2050 – long-term development vision^{6b}, emphasizing rural diversification, climate adaptation, sustainable land governance, and inclusive socioeconomic development (2020–2050)^{6c}. Each pathway includes an export-enhanced variant (PW1–PW3 + Export), reflecting the potential role of moderate meat exports in reducing grazing pressure, improving livestock-derived economic revenues, and supporting long-term sustainability. Full model parameters and assumptions are detailed in the Methods section.

¹ANPP: Simulated aboveground net primary productivity, used as an indicator of rangeland productivity available for harvesting.

²Household vehicle ownership.

³Based on the previous year's mortality from the dzud model.

⁴Constant at 94×10^3 SU/year (10-year average: 2015–2024).

⁵Meat exports are projected as increase by 0.98% of the total POP per year (10-year average: 2015–2024).

⁶Regression model based on historical HPOP ($R^2 = 0.90$).

⁷Household vehicle ownership projected based on GDP under SSPs and Vision 2050 economic growth targets.

⁸HPOP and GDP based on SSPs and Vision 2050 economic growth targets.

⁹Meat exports are increased by logistic growth of total POP under ecologically and biologically sustainable conditions to ensure realistic projections (See Methods).

Multi-hazards are defined by the combination of summer drought and winter severity (extreme cold temperatures and heavy snow), which together restrict pasture availability and accessibility. Summer drought reduces rangeland productivity, depletes hay supplies, and weakens livestock body condition by preventing adequate pre-winter fattening. Severe winter conditions further restrict grazing time and energy intake, leading to mortality from starvation. Hazards were quantified using a *dzud hazard index*^{28,48}, derived from bias-corrected, downscaled projections (1971–2050) of five Earth System Models (ESMs), participating in the Coupled Model Inter-comparison Project Phase 6 (CMIP6)⁴⁴. Socioeconomic vulnerability is defined as pre-winter coping capacity, determined by the livestock population (POP) and hay preparedness. In our *dzud* risk study⁸, the strongest vulnerability factors explaining mortality variations during 2000–2014 were hay preparedness (18.3%), POP (17.6%), and vehicle-based transportation capacity (3.3%); these were adopted as primary vulnerability indicators for future projections. Livestock condition is linked to the rangeland carrying capacity^{8,29}, which declines as POP increases. This pattern is well documented in Mongolia, where POP has increased approximately 2.5-fold since 1990, surpassing national carrying capacity and contributing to rangeland degradation^{38,41,49,50}. POP dynamics were simulated using a herd-growth model⁵¹, incorporating data on births (1991–2023), mortality from *dzud* (1970–2024) and disease (1991–2020), and offtake—domestic consumption (2003–2023) and exports (2003–2023)—sourced from the National Statistical Office (NSO)⁵². Domestic meat demand was projected as a function of gross domestic product (GDP) growth and human population change, mediated through income elasticity⁵³. Hay preparedness was modelled as a function of forage availability and household harvesting capacity. Forage availability was estimated using simulated ANPP (aboveground net primary productivity) from the process-based ecosystem model Organising Carbon and Hydrology in Dynamic Ecosystems–Grassland Management version 3.2 (ORCHIDEE-GM v3.2)⁵⁴. Household harvesting capacity was estimated from vehicle ownership data (number of cars and tractors, 2001–2023)⁵², serving as a dual proxy for hay harvesting and fodder procurement capacity. Future vulnerability was projected across six national socioeconomic pathways (PW1–PW3 and PW1–PW3+Export). By integrating climate projections with ecological and socioeconomic dynamics, this study presents the first system-wide assessment of *dzud* risk under multiple scenarios, providing actionable insights for climate adaptation, rangeland governance, and sustainable development policy in dryland pastoral systems.

Results

Historical *dzud* dynamics: climate hazards and socioeconomic vulnerability

Dzud-induced mortality increased markedly during 1971–2024 ($Z = -2.69$, $p < 0.01$; Mann–Kendall test), with particularly severe events concentrated in the 2000s (Fig. 1b). During 2000–2024, *dzuds* caused approximately 100.3 million livestock deaths (sheep units, SU). The most significant mortality events were in 2000–2002 (26.6 million SU; 10–22% of the national herd), in 2010 (25.5 million SU; 22%), and in 2023–2024 (23.8 million SU; 7–12%). The integrated model effectively reproduced historical patterns, exhibiting significant correlations for livestock mortality ($r = 0.79$, $p < 0.05$), hay preparedness ($r = 0.84$, $p < 0.05$), and livestock population trends ($r = 0.97$, $p < 0.05$) (Figs. 1b, d, e).

The *dzud* hazard index shows a significant increasing trend over the study period ($Z = 2.41$, $p < 0.05$), attributable primarily to escalating summer drought frequency and intensity ($Z = 2.89$, $p < 0.01$; Fig. 1c). Winter severity, by contrast, showed no statistically significant trend ($Z = -0.69$, $p > 0.05$). Concurrently, structural socioeconomic shifts amplified vulnerability. Following livestock privatisation in the early 1990s, POP increased significantly ($Z = 6.48$, $p < 0.001$), while hay preparedness per animal (SU) declined by 33.7% relative to the pre-1990 baseline ($Z = -3.30$, $p < 0.001$; Fig. 1e). Together, these dynamics substantially eroded the adaptive capacity of the livestock system to cope with climatic shocks.

POP dynamics were governed by births, *dzud*- and disease-related mortality, and offtake for domestic consumption and export markets (Fig.

1e). POP increased from approximately 55 million SU in 1990 to 110 million SU in 2024, following livestock privatisation in the early 1990s. This two-fold expansion coincided with a four-fold increase in offtake, driven primarily by rising domestic meat demand linked to human population growth. Total slaughter offtake peaked in 2020 at approximately 27 million SU (29.7% of POP), coinciding with disruptions associated with the COVID-19 pandemic (Fig. 1e). In contrast, meat exports remained negligible, ranging from 0.1% to 2.0% of POP, peaking in 2018–2019, declining during the pandemic, and only partially recovering by 2023. Disease-related mortality steadily declined from 1.6% in 1990 to below 0.05% by 2024. Overall, domestic consumption remained the dominant driver of livestock offtake throughout the period, reflecting the persistent primacy of local demand over export-oriented market development.

Future *dzud* risk under climate and socioeconomic scenarios

Ensemble projections from five ESMs indicate a substantial increase in *dzud* risk across all climate scenarios and socioeconomic pathways, intensifying from the mid-2030s (Fig. 3a). During 2036–2050, *dzuds* are projected to occur nearly annually, totalling 13–15 events. Under the high warming scenario (SSP5–8.5), *dzud*-related mortality is projected to peak at 49.5 million SU in the 2040s. The relatively modest variation in mortality across socioeconomic pathways suggests that climate hazards are the primary driver of risk. All climate scenarios project an exacerbation of drought conditions, particularly under medium-to-high warming scenarios (SSP3–7.0 and SSP5–8.5) (Fig. 3b). Regionally, southwestern areas are projected to experience the most significant impacts (Fig. S1). These conditions are associated with regional air temperature increases of +2.3 °C to +2.9 °C and precipitation reductions of −7.4% to −10.1%, with decreases of up to −30% in western and central-eastern regions (Figs. S2, S3). Winter severity exhibits regional variability (Fig. S4); however, snowfall is projected to increase substantially—by +24.7% to +29.5% across all scenarios (Fig. S2)—with local maxima reaching up to +80% in western regions (Fig. S4). The combination of intensifying drought and increasing snowfall represents compound multi-hazard conditions that collectively elevate mortality risk from the mid-2030s onward.

Regarding vulnerability, POP is projected to increase steadily, surpassing 170 million SU by the early 2040s (Fig. 3c). Although SSP1–2.6 exhibits slightly lower growth, variations among pathways remain relatively modest. Growth is highest under SSP3–7.0 and PW1 (business-as-usual) and lowest under SSP5–8.5 and PW2 (national trends aligned with global SSPs), where elevated climate-induced mortality partially offsets POP expansion. Domestic meat demand is projected to increase by 60.7–82.2%, driven by human population growth (up to +52.3%) and GDP expansion (up to 5.4×) across pathways (Fig. S5). Despite a projected increase in total hay preparedness across all scenarios (Fig. S6)—attributable primarily to enhanced rangeland productivity (ANPP) and greater household vehicle ownership linked to GDP growth (Fig. S6)—per-animal hay availability is projected to decline as POP continues to expand (Fig. 3c). Hay deficits in *dzud* years are projected to reach 12.5–24.2% below the historical average (2005–2024), exacerbating nutritional stress and ultimately driving livestock mortality.

Livestock-derived economic revenues are projected to increase by 22.2–27.4% during 2025–2035 relative to the historical baseline (2020–2024), before declining after the mid-2030s—particularly under the high warming scenario (SSP5–8.5). Under the business-as-usual pathway (PW1), revenue is projected to fall by approximately 25% in the early 2040s, driven by escalating climate hazards, persistent POP growth, and continued grazing pressure. These dynamics collectively amplify climate-related risks and compound economic instability. The inter-model variability across ESM precipitation projections (Fig. 3) generates a range of outcomes for mortality and revenue, underscoring the sensitivity of projections to future climate uncertainty.

Reducing climate change risk and enhancing resilience

Export-enhanced pathways (PW1–PW3+Export) gradually increase the meat export share from the historical baseline (PW1–PW3) (0.98% of POP,

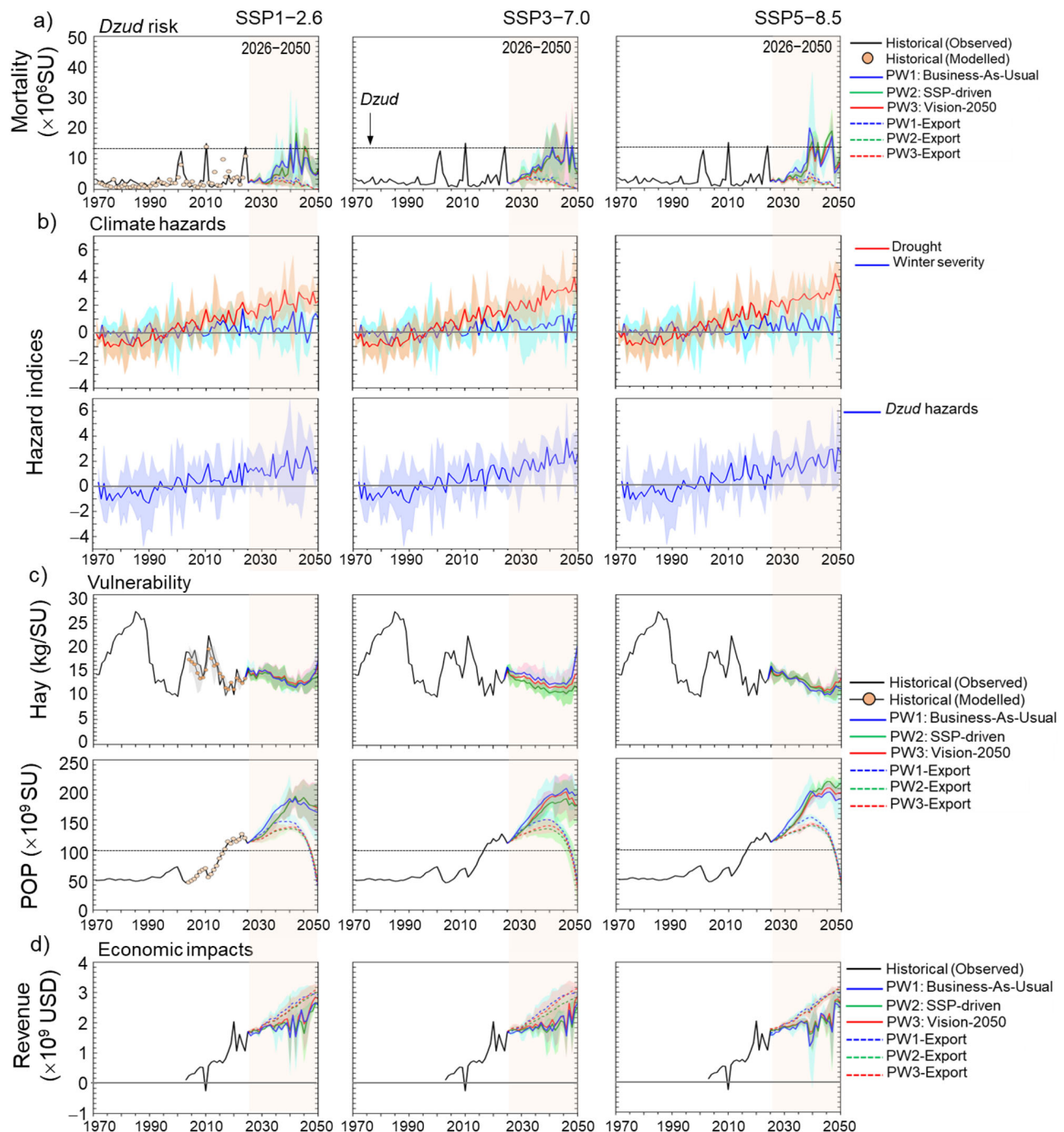


Fig. 3 | Observed (1971–2024) and projected (2025–2050) livestock mortality (*dzud* risk) and economic impacts with key contributing factors. Projections from five ESMs under three climate scenarios (SSP1–2.6, SSP3–7.0, and SSP5–8.5) and three socioeconomic pathways: PW1 (Business-as-Usual), PW2 (SSP-aligned trends), and PW3 (Vision 2050) and their export-enhanced variants (PW1–PW3+Export).

a Observed and modelled mortality (sheep units, SU); dashed line marks the *dzud* threshold at 10 million SU. **b** Climate hazards. **c** Herder vulnerability: hay preparedness (kg/SU) and livestock population (POP); **c** dashed line is mean rangeland carrying capacity (103 million SU, 2000–2019). **d** Economic impacts of *dzuds*. Solid lines show ensemble means across ESMs; coloured shading indicates the interquartile range.

2015–2024) to scenario-specific targets by 2050 (PW1: 6.5%, PW2: 5.5%, PW3: 5.8%) (Table 1) designed to keep POP below rangeland carrying capacity (Fig. 3). This trajectory aligns with policy simulations⁴¹, suggesting that a gradual export growth, combined with complementary regulatory measures such as pasture taxation, can reduce POP while improving sector value. In practice, this requires coordinated investment in veterinary certification^{55,56}, traceability systems, cold-chain infrastructure⁵⁷, and herder cooperatives⁵⁸—rather than treating export expansion as an isolated market-opening initiative. Among all pathways, export-enhanced pathways

yielded the most ecologically and economically favourable outcomes, substantially reducing *dzud*-related mortality, stabilizing POP, and increasing livestock-derived revenues despite escalating climate risks (Fig. 3c). A gradual annual increase in meat exports stabilizes POP by the early 2040s, followed by a decline below the rangeland carrying capacity threshold^{38,59}. Despite inter-model variability, export-enhanced pathways consistently reduce overstocking and advance the pastoral system toward ecological sustainability, reducing annual mortality from 8–11 million SU under three baseline pathways (PW1–PW3) to 1–3 million SU—preventing an

estimated 6.0–9.5 million animal deaths (SU) annually during 2036–2050 (Fig. 4a). Correspondingly, economic performance improves substantially under PW1–PW3+Export (Fig. 3d), with meat revenues projected to increase by 9.2–25.4% under PW1+Export, 33.2–36.3% under PW2+Export, and 27.6–34.1% under PW3+Export relative to 2024 levels—an overall range of 9.2–36.3% across all export-enhanced pathways. Collectively, these findings demonstrate that market-oriented offtake strategies can generate substantial economic co-benefits while simultaneously improving ecological resilience.

Together, these results indicate a significant divergence between baseline pathways (PW1–PW3) and export-enhanced pathways (PW1–PW3+Export) (Fig. 3). Continued POP growth and escalating climate hazards amplify *dzud* risk, intensify grazing pressure on rangelands, and undermine long-term livestock-derived revenue stability under baseline pathways. In contrast, export-enhanced pathways present a viable route to ecological balance, reduced vulnerability, and enhanced livestock system resilience. Capturing these benefits requires coordinated policy action across multiple sectors, including investment in veterinary services, traceability and cold-chain infrastructure, inclusive market platforms, and rangeland governance frameworks.

Discussion

Dzud risk is inherently multifaceted risk influenced by the intersection of climatic^{8,30}, ecological^{26,29}, and socioeconomic^{8,28} factors. This study presents one of the first national-scale, scenario-based projections of future *dzud* dynamics, integrating multiple climate scenarios and socioeconomic pathways. Our projections indicate a marked increase in *dzud* mortality from the mid-2030s, driven by escalating multi-hazards (summer droughts and snowy winters), consistent with wider regional patterns^{60,61}. Climate forcing alone does not fully explain projected *dzud* intensification; persistent overstocking emerges in all pathways as a primary amplifier of vulnerability. Across all baseline pathways (PW1–PW3), projected POP is anticipated to surpass rangeland carrying capacity³⁸ by more than twofold by the 2040s, further diminishing ecological resilience—already deteriorated approximately 70%^{26,50,62}. POP expansion is sustained by consistently elevated birth rates (~31%), low export offtake (0.98%), and negligible disease-related mortality (0.08%), resulting in demographic inertia. Beyond demographic pressures, future disease risks may intensify as climate change alters vector distribution (e.g., ticks, mosquitoes)⁶³ and heat stress compromises immune function⁶⁴, introducing additional sources of livestock mortality not captured in baseline projections.

While our analysis operates at the national scale, *dzud* vulnerability also manifests through household-level asset dynamics that warrant acknowledgement. Research at the herding household level indicates that vulnerability is not uniformly distributed across households: those near the minimum viable herd size threshold face the greatest risk, as losses push them below the recovery threshold, while households with larger herds retain buffers against mortality events^{8,65,66}. However, our national-level POP data do not permit direct disaggregation of *dzud* impacts by household herd size, and explicitly modelling this multi-scale relationship remains a priority for future research. Furthermore, *dzud* may transiently reduce grazing pressure in regions with low and variable precipitation (e.g., desert-steppe), where climate rather than livestock density drives vegetation productivity (non-equilibrium dynamic)^{57,68}. However, relying on this regulatory function as a management strategy is inadequate⁶⁶: episodic climate-induced mortality events imposes catastrophic and inequitable losses on herding households, rather than providing a predictable or controllable regulatory mechanism⁶⁸. Moreover, national-scale data demonstrate that post-*dzud* herd recovery is generally achieved within two to six years (Fig. 1e), depending on event severity and species composition^{69,70}. These rapid recovery underscores the perpetuation of *dzud* risk⁸, highlighting the need for structural interventions—such as planned destocking, regulated mobility, and market-based offtake^{16,34,71}—rather than reliance on climate-induced mortality as a POP regulation mechanism.

Hay preparedness is widely advocated as a fundamental adaptation strategy^{8,28,47}. Projections indicate a modest increase in hay preparedness, attributable to increasing ANPP and expanded household harvesting capacity associated with GDP growth. The projected increase in ANPP—as simulated by ORCHIDEE-GM—is partly driven by elevated atmospheric CO₂ concentrations⁷², which enhance plant photosynthesis and water-use efficiency⁷³. Nevertheless, per-animal hay availability is projected to decline primarily as a consequence of POP expansion, while infrastructure and revenue disparities—particularly under SSP3–7.0 (regional rivalry⁴⁵)—further constrain hay preparedness in lower-income regions. Moreover, hay reserves constitute as a temporary buffer rather than a structural solution, as they do not address the proximate drivers of *dzud* vulnerability, namely chronic overstocking and rangeland degradation. Achieving sustainable adaptation therefore necessitates aligning POP with rangeland carrying capacity thresholds, ensuring equitable access to preparedness resources, and embedding adaptation within effective governance frameworks^{15,74}.

Long-term sustainable pastoralism requires balancing ecological resilience, socioeconomic viability, and cultural continuity^{75,76}. Historically, traditional adaptation strategies—including mobility, collective labour exchange, and strategic hay storage—have buffered pastoral systems against climate variability^{77,78}. However, escalating climate shocks^{8,30}, rangeland degradation^{50,62}, rural inequality⁷⁸, and youth outmigration⁷⁹ have increasingly eroded these social-ecological systems, necessitating transformative adaptation that aligns pastoral land use with ecological limits, revitalises traditional knowledge, and integrates climate information into governance frameworks. Our results demonstrate that export-enhanced pathways offer a viable route to stabilising POP below carrying capacity and reducing *dzud* mortality, while simultaneously enhancing revenues—suggesting that ecological resilience and socioeconomic productivity are potentially mutually reinforcing. Market-oriented offtake may redirect herder incentives away from herd size maximisation toward per-animal value, higher export returns may enable herders to meet revenue targets with reduced herd sizes^{41,80,81} thereby alleviating grazing pressure, prioritising livestock quality over quantity—provided that complementary regulatory mechanisms and inclusive market governance are in place^{41,82,83}. We acknowledge, however, that this outcome is not automatic: herders have historically responded to market opportunities through herd accumulation rather than reduction^{84,85}, underscoring that robust institutional frameworks must accompany export promotion to prevent perverse incentives that drive further herd accumulation.

Export-enhanced pathways face substantial implementation challenges, particularly with respect to animal health regulations, trade certification, and logistics⁸⁶. Entry into high-value export markets requires compliance with stringent sanitary and phytosanitary standards, most critically regarding Foot-and-Mouth Disease (FMD) certification⁸⁷, necessitating continuous investment in veterinary services, epidemiological surveillance, and cross-border biosecurity measures. Mongolia has achieved a marked reduction in disease-related livestock mortality, with deaths declining to below 0.08% by 2024. Maintaining FMD-free status and meeting international certification standards will require sustained investment in veterinary services, epidemiological monitoring⁸⁸, and cross-border biosecurity protocols^{89,90}. Equally essential are the development of cold-chain logistics, meat traceability systems, and the strategic positioning of Mongolia's grass-fed, pasture-based production systems as a premium market brand^{91–94}. Export growth must be firmly grounded in ecological sustainability^{91,92} and deliberately designed to mitigate rural inequality and over-reliance on volatile international markets—necessitating coordinated policy frameworks that encompass ecological monitoring, herd size regulation, veterinary governance, and infrastructure development.

Our framework reproduces historical *dzud* dynamics reasonably well but is subject to several limitations. First, the model overestimates mortality in 2016, likely due to the exclusion of emergency response and humanitarian relief interventions⁹⁵. Notably, the 2016 winter hazards had substantial impacts on wildlife, particularly *Saiga tatarica mongolica* and *Gazella subgutturosa*⁹⁶. Second, the model does not disaggregate to the provincial

level, constraining the representation of spatial variations in vulnerability. Third, the national socioeconomic pathways (PW2)⁴⁴ may insufficiently capture local-level factors such as political structures, cultural norms, and infrastructure quality. Fourth, climate model uncertainty—notably wet biases⁹⁷ in certain CMIP6 models (e.g., UKESM1-0-LL)—may lead to overestimation of future forage availability. Fifth, hay preparedness proxies require careful contextualisation across Mongolia's diverse ecological zones. Vehicle ownership serves as a dual proxy for harvesting capacity and market-access mobility^{8,28,47}; however, in desert-steppe zones, local hay production is constrained, and herders rely more heavily on market-sourced fodder—a distinct coping mechanism^{8,28} not captured in the current model. Furthermore, ORCHIDEE-GM does not simulate changes in vegetation composition, nutrient cycling, or long-term biodiversity feedbacks that may be critical under elevated CO₂ scenarios⁹⁸. Future research should employ multi-model ecological ensembles, integrate local governance factors, and develop high-resolution socioeconomic pathways to strengthen adaptation planning and policy relevance.

Our results suggest that Mongolian pastoralism is approaching a critical threshold of systemic risk, beyond which ecological and socioeconomic recovery may become increasingly difficult under climate change. Transformative adaptation is attainable but demands coordinated institutional action—encompassing veterinary services, cold-chain logistics, equitable land tenure, herder collectives, and equity-sensitive policy design—underpinned by effective governance and inclusive market mechanisms. Export promotion must be integrated into comprehensive institutional transformation—including pasture taxation⁴¹, price transmission to herders⁸⁰, transparent procurement, and benefit-sharing arrangements—to prevent market intermediaries from capturing a disproportionate share of the export-generated value and to ensure that productivity gains translate directly into improved herder livelihoods. The integrated climate–rangeland–society framework developed here is applicable to comparable dryland pastoral systems in Central Asia—including Kazakhstan and Kyrgyzstan—where policy experiences in export promotion, rangeland management, and climate adaptation provide valuable comparative insights^{99–102}. Kazakhstan's experience demonstrates that success hinges on investment in veterinary infrastructure, food safety certification, and inclusive market governance^{99,102}—underscoring that export promotion must be embedded within robust regulatory frameworks that support herder mobility, equitable market access, and rangeland health. Finally, sustaining pastoral livelihoods and ecosystem integrity amid accelerating climate and socioeconomic change demands that market development be firmly grounded in ecological limits and inclusive governance, and the long-term wellbeing of herding communities^{103,104}.

Methods

Dzud risk modelling framework

Livestock mortality (Fig. 2) during the cold season (November–March) was simulated using a previously validated Poisson multi-regression (PMR) model⁸ developed from historical *dzud* events (2000–2014). The model integrates multi-hazard indices (summer drought and winter severity) and vulnerability factors (POP and hay preparedness) across climate and socioeconomic scenarios through 2050. A severe *dzud* year is defined as one in which mortality exceeds 10.6 million SU, based on the average of six major *dzud* events recorded in the 2000s. The PMR model demonstrated substantial explanatory power, with multi-hazards (47.3%) and vulnerability (46.2%) collectively accounting for 93.5% of mortality variation, alongside robust predictive accuracy ($Q^2 > 0.9$)⁸. Livestock mortality was modelled as count data following a Poisson distribution with a log-link function (Eq. 1), where the dependent variable denotes total mortality across five species (sheep, goats, cattle, horses, and camels), converted to sheep units (SU) to enable interspecies comparison by accounting for differences in feed requirements and body mass:

$$\text{Mortality} = \exp(\beta_0 + \beta_1 S_{\text{summer}} + \beta_2 S_{\text{winter}} + \beta_3 \text{POP} - \beta_4 \text{HAY}) \quad (1)$$

where S_{summer} and S_{winter} denote multi-hazard indices for summer (May–August) drought and winter (November–March) severity (Eqs. 2 and 3), respectively; POP is the pre-winter livestock population (SU); HAY is the hay preparedness per SU; and β_{1-4} are the regression coefficients. Both indices (Eqs. 2 and 3) follow an identical standardised anomaly structure, applied to their respective seasonal windows:

$$S_{\text{summer}} = \frac{\Delta T}{\sigma_T} - \frac{\Delta P}{\sigma_P} \quad (2)$$

$$S_{\text{winter}} = \frac{\Delta T}{\sigma_T} - \frac{\Delta P}{\sigma_P} \quad (3)$$

where T and P denote monthly temperature and precipitation; $\Delta T = T - T_m$ and $\Delta P = P - P_m$ are anomalies from the climatological averages (1971–2000); and σ_T and σ_P are the corresponding standard deviations. Values of $S_{\text{summer}} > 0$ indicate drought conditions, while $S_{\text{winter}} < 0$ indicates severe winter conditions. Multi-hazards were quantified using a composite *dzud* hazard index⁴⁸ (Eq. 4), which captures the cumulative effects of a hot, dry summer (drought) followed by cold, snowy winters (Eqs. 2 and 3). A high ΔS indicates hazardous *dzud* conditions:

$$\Delta S = S_{\text{summer}} - S_{\text{winter}} \quad (4)$$

Historical vulnerability was estimated using observed POP and hay preparedness. Future vulnerability was projected under six socioeconomic pathways (PW1–PW3 and PW1–PW3+Export; Table 1), in conjunction with three climate scenarios (SSP1–2.6, SSP3–7.0, and SSP5–8.5). Hay preparedness was modelled based on rangeland productivity and household harvesting capacity, validated against observed data ($R^2 = 0.86$) (Fig. 3c). Forage availability was represented by simulated ANPP using ORCHIDEE-GM v3.2⁵⁴, a process-based ecosystem model designed to simulate carbon, water, and energy fluxes across scales ranging from local to global^{105–107}, with a specific focus on grassland management⁵⁴. The model has been previously validated against the observed rangeland vegetation productivity and greenness indices, demonstrating good spatiotemporal agreements across Mongolia^{16,108}. ORCHIDEE-GM v3.2 was applied over Mongolia at a spatial resolution of $0.5^\circ \times 0.5^\circ$ for 1901–2050, driven by observed climate data and bias-corrected projections from five CMIP6 ESMs under three climate scenarios, assuming full C3 grass coverage and 12 USDA soil texture classes. A spin-up simulation using 1901–1910 climate conditions ensured carbon pool equilibrium. Household harvesting capacity was estimated using national-level vehicle ownership data (cars and tractors) as a proxy for hay-harvesting and winter feed storage capacity, with future ownership projected using a logistic growth model based on GDP trajectories. Historical trends were extrapolated using PW1 ($R^2 = 0.84$), while PW2 and PW3 were adjusted to align with pathway-specific GDP growth trajectories.

POP was projected using a herd-growth model⁵¹, estimating POP at time $t + 1$ by accounting for natural growth and offtake reductions (Eq. 5):

$$\text{POP}_{t+1} = (1 + \text{Birth} - \text{Mortality}) \times \text{POP}_t - \text{Offtake} \quad (5)$$

Offtake was defined as the ratio of POP removed by slaughter for export and domestic meat consumption (C_D) to the current POP (POP_t) (Eq. 6).

$$\text{Offtake} = \frac{\text{Slaughter}(\text{Export} + C_D)}{\text{POP}_t} \quad (6)$$

Future birth rates were projected using a regression model based on the preceding year's POP and mortality ($R^2 = 0.95$). Disease-related mortality was held constant at 94×10^3 SU/year, based on the 10-year average (2015–2024). The domestic meat demand was projected using a dynamic income elasticity model⁵³, integrating GDP growth and human population

change (Eq. 7).

$$C_D = C_{D-P} + (C_{D-P} \times D_P(1 + D_M)) \quad (7)$$

where C_{D-P} is the previous year's domestic consumption C_D (SU), D_P is the total meat demand in the previous year (SU), and D_M is the yearly meat demand growth rate under the assumption of perfectly elastic supply (Eqs. 8 and 9):

$$D_M = \text{Income Elasticity} \times \text{GDP} \quad (8)$$

$$\text{Income Elasticity} = 0.1632 - 0.0938 \times \frac{\text{GDP}}{\text{HPOP}} \quad (9)$$

where GDP is the GDP growth rate and HPOP is the human population.

Annual meat export volumes were projected by multiplying the projected POP by an evolving export share, with a baseline of 0.98% derived from the 10-year average (2015–2024). The average rangeland carrying capacity was set at 0.93 SU/ha (2000–2019), corresponding to a national limit of approximately 103 million SU across 110.8 million hectares^{47,48}. For export-enhanced pathways, the export share was projected using a logistic growth model (Eq. 10):

$$\text{LogisticExport}_t = I + \frac{G_{tr}}{1 + e^{-k(t-t_0)}} \quad (10)$$

where I is the initial export ratio (0.98%), G_{tr} is the pathway-specific target export share by 2050 (PW1: 6.5%, PW2: 5.5%, and PW3: 5.8%), k is a growth rate constant ($k = 0.187$). t is the projection year (2025–2050), t_0 is the inflection year (2037). The same SSP×pathway combinations were applied across all ESMs to capture the full range of climate–socioeconomic futures.

Total economic revenue was estimated by combining revenue from domestic and export meat sales and subtracting losses attributable to livestock mortality. Meat production was calculated based on total offtake, assuming an average carcass weight of 20 kg per SU. Future meat prices were maintained at 2024 levels throughout the projection period (2025–2050), applied separately for domestic and export sales across all scenarios and pathways. Mortality losses—those from *dzuds*—were quantified in financial terms based on the value of lost meat production from deceased animals, ensuring that net revenue captured both production outputs and climate-related risks to pastoral livelihoods.

Datasets

Gridded climate data (air temperature and precipitation) at a spatial resolution of $0.5^\circ \times 0.5^\circ$ were used for multi-hazard assessment and as forcing for ecosystem model. Observed climate data for 1971–2022 were sourced from CRU TS v4.07 (Climatic Research Unit Time Series, version 4.07)¹⁰⁹. Future climate conditions (up to 2050) were derived from downscaled and bias-corrected datasets from ISIMIP3b¹¹⁰, obtained from five CMIP6 ESMs under three scenarios (SSP1–2.6, SSP3–7.0, and SSP5–8.5). Bias adjustment and statistical downscaling were performed using ISIMIP3BASD v2.5.0 with the W5E5 v2.0 observational baseline, following the procedures outlined in the ISIMIP3b documentation⁴⁴. The five ESMs were selected to represent a diverse range of climate sensitivities within the CMIP6 ensemble, comprising three lower-sensitivity models (GFDL-ESM4, MPI-ESM1-2-HR, and MRI-ESM2-0) and two higher-sensitivity models (IPSL-CM6A-LR and UKESM1-0-LL). This ensemble design ensured a robust representation of potential climate futures.

POP and *dzud*-related mortality data for 1971–2024 were sourced from the NSO⁵², which conducts comprehensive annual livestock censuses every December, providing species-specific POP counts for horses, cattle, sheep, goats, and camels. To ensure consistency in feed demand calculations and integration into the modelling framework, all species were converted into standardised livestock units (sheep unit: SU) using widely accepted conversion factors²⁹: 1 camel = 5 SU, 1 horse = 7 SU, 1 cattle = 6 SU, 1 sheep

= 1 SU, and 1 goat = 0.9 SU. Relative mortality rates were calculated as the ratio of animals that died during the cold-season to the pre-winter POP. Disease-related mortality (1991–2024) and birth rates (surviving offspring) (1991–2022) were also incorporated. These variables were essential for modelling POP dynamics, estimating vulnerability, and calibrating POP changes within the *dzud* risk assessment framework.

Pre-winter socioeconomic data obtained from the NSO (1999–2023⁵²) included household vehicle ownership (cars and tractors; 1990–2023), hay preparedness per livestock unit (kg/SU; 1972–2023), domestic meat consumption (2003–2023), meat export volumes (2003–2023), GDP (1980–2023), and human population (1980–2024). Projections for human population and GDP under PW1 and PW3 were obtained from the World Bank¹¹¹ and Vision 2050⁴⁶, respectively; PW2 projections were sourced from ISIMIP3b⁴⁴ under three SSPs. Domestic sheep meat prices and export horse meat prices served as proxies for domestic and export market values, respectively.

Data availability

The bias-corrected climate model outputs are available at <https://data.isimip.org/search/tree/ISIMIP3b/InputData/climate/>. Socioeconomic data are available from the National Statistics Office of Mongolia (www.1212.mn).

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Author contributions

B.N. and M.S. conceptualised the research, with inputs from S.O.; and B.N. performed the analyses, and wrote the manuscript with contributions from J.C., M.S., C.P.O.R., S.O., and B.A. J.C. and C.P.O.R. provided the climate projections. J.C. conducted ecosystem model simulations. S.O. contributed to the development of the meat consumption module. B.A. and J.D. contributed to the collection of socioeconomic and livestock data.

Competing interests

The authors declare no competing interests.

Additional information

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