



# Climate change drives a decline in global grazing systems

Chaohui Li<sup>a,b,1</sup> , Maximilian Kotz<sup>a,c</sup>, Prajal Pradhan<sup>a,d</sup> , Xudong Wu<sup>a,e</sup>, Yuanchao Hu<sup>a,f</sup>, Zhi Li<sup>b</sup>, and Guoqian Chen<sup>b,g,1</sup>

Affiliations are included on p. 9.

Edited by Nils Stenseth, Universitetet i Oslo, Oslo, Norway; received November 27, 2025; accepted December 23, 2025

Grazing systems represent the most extensive production systems in the world and are highly sensitive to climate change. However, their global-scale sensitivity and vulnerability to climate impacts remain poorly understood. Here, we apply the safe climatic space framework to assess how changes in core climatic drivers of grazing suitability, including temperature, precipitation, humidity, and wind speed, will reshape global grassland-based grazing systems. Our analysis projects a net decline of 36 to 50% of areas in climate suitability for grazing by 2100, accompanied by inter- and intracontinental shift of grazing suitability. These changes are expected to negatively affect 110 to 140 million pastoralists and 1.4 to 1.6 billion livestock, with particularly severe impacts in Africa. We further show that 51 to 81% of these impacted populations reside in countries with low income, serious hunger, severe gender inequality, and high political fragility. Our study implies that future climate change will threaten grazing suitability across large portions of Earth, endangering the livelihoods of numerous communities and potentially triggering widespread socioeconomic consequences.

climate change impacts | safe climatic space | grazing systems | inequality

Climate change is one of the greatest threats to human subsistence in the 21st century, affecting countless people and extensive ecosystems (1–4). Grazing systems are highly sensitive and vulnerable to these widespread environmental changes given its high reliance on natural processes, such as heat, water, and forage (5, 6). These systems, spanning every continent and covering a third of the Earth's surface, represent the largest production system globally and are uniquely exposed to vast, diverse, and highly heterogeneous climate impacts (7–10). Despite its importance, climate change's impacts on grazing systems remain unclear at a global scale.

These challenges mainly stem from three interrelated complexities. First, grazing systems are influenced by diverse climatic factors, such as precipitation, temperature, and humidity (11–14). For example, studies have shown that grassland vegetation is sensitive to elevated CO<sub>2</sub> (15–17) and shows complex responses to shifting precipitation patterns and variability (18–20). Livestock themselves exhibit thermal tolerances beyond which their productivity declines (21). While valuable for understanding key mechanisms, an overview of their potential combined effects remains challenging, as studies often focus on specific regions (22) or only a single impact channel. By contrast, future livestock systems will be increasingly exposed to a range of changing climatic conditions, such as temperature, precipitation, humidity, wind speed, etc. (23), highlighting the importance and challenges of a holistic approach to evaluating the impact of climate change.

Second, these climate factors are projected to shift in divergent directions and magnitudes across regions (19, 24)—some areas may experience elevated temperatures coupled with precipitation declines, while others exhibit the reverse. Third, even when the direction and gradient of change is consistent, outcomes can be divergent due to regional heterogeneity (15–17)—for example, rising temperatures may improve grazing potential on the Tibetan Plateau while creating challenges in the Saharan savanna. This complex interplay of variable dynamics, climatic gradients, and regional heterogeneity underscores the challenges of assessing the impacts of climate change on grazing systems at a global scale.

Here, we adopt a safe climatic space (25, 26) approach to provide a holistic evaluation of how shifts in multiple conditions could alter grassland-based extensive grazing systems (hereafter known as grazing systems) globally. This approach measures the climatic conditions under which the current grazing system can persist, by statistically linking observed occurrences with climate variables, and then evaluates the extent to which future change will drive systems away from these conditions. As such, this approach can consider multiple drivers and account for their heterogeneous effects across different regions, depending on their position within the multidimensional space of suitable conditions, thereby addressing the aforementioned complexities. Moreover, we build on this framework to examine the socioeconomic implications of climate change impacts on grazing systems. Although rarely

## Significance

Grazing systems form critical livelihood bases for hundreds of millions of people across diverse ecological and socioeconomic contexts, yet we lack a global understanding of their sensitivity to climate change. Applying a “safe climatic space” framework, we project a 36 to 50% contraction in suitable grazing areas by 2100 due to future climate change. We show the loss of safe climatic space for grazing overlaps significantly with regions already suffering from severe poverty, hunger, and political fragility. We estimate this could displace the livelihoods of over 100 million pastoralist and 1.4 billion livestock. These findings highlight how climate change will compound existing inequalities, threatening to destabilize the world's most extensive food production system and the communities that depend on it.

Author contributions: C.L. designed research; C.L. performed research; C.L., M.K., P.P., X.W., Y.H., Z.L., and G.C. contributed new reagents/analytic tools; C.L., M.K., P.P., and G.C. analyzed data; and C.L., M.K., Y.H., and G.C. wrote the paper.

The authors declare no competing interest.

This article is a PNAS Direct Submission.

Copyright © 2026 the Author(s). Published by PNAS. This article is distributed under [Creative Commons Attribution-NonCommercial-NoDerivatives License 4.0 \(CC BY-NC-ND\)](#).

PNAS policy is to publish maps as provided by the authors.

<sup>1</sup>To whom correspondence may be addressed. Email: [lichao@pku.edu.cn](mailto:lichao@pku.edu.cn) or [gqchen@pku.edu.cn](mailto:gqchen@pku.edu.cn).

This article contains supporting information online at <https://www.pnas.org/lookup/suppl/doi:10.1073/pnas.2534015123/-/DCSupplemental>.

Published February 9, 2026.

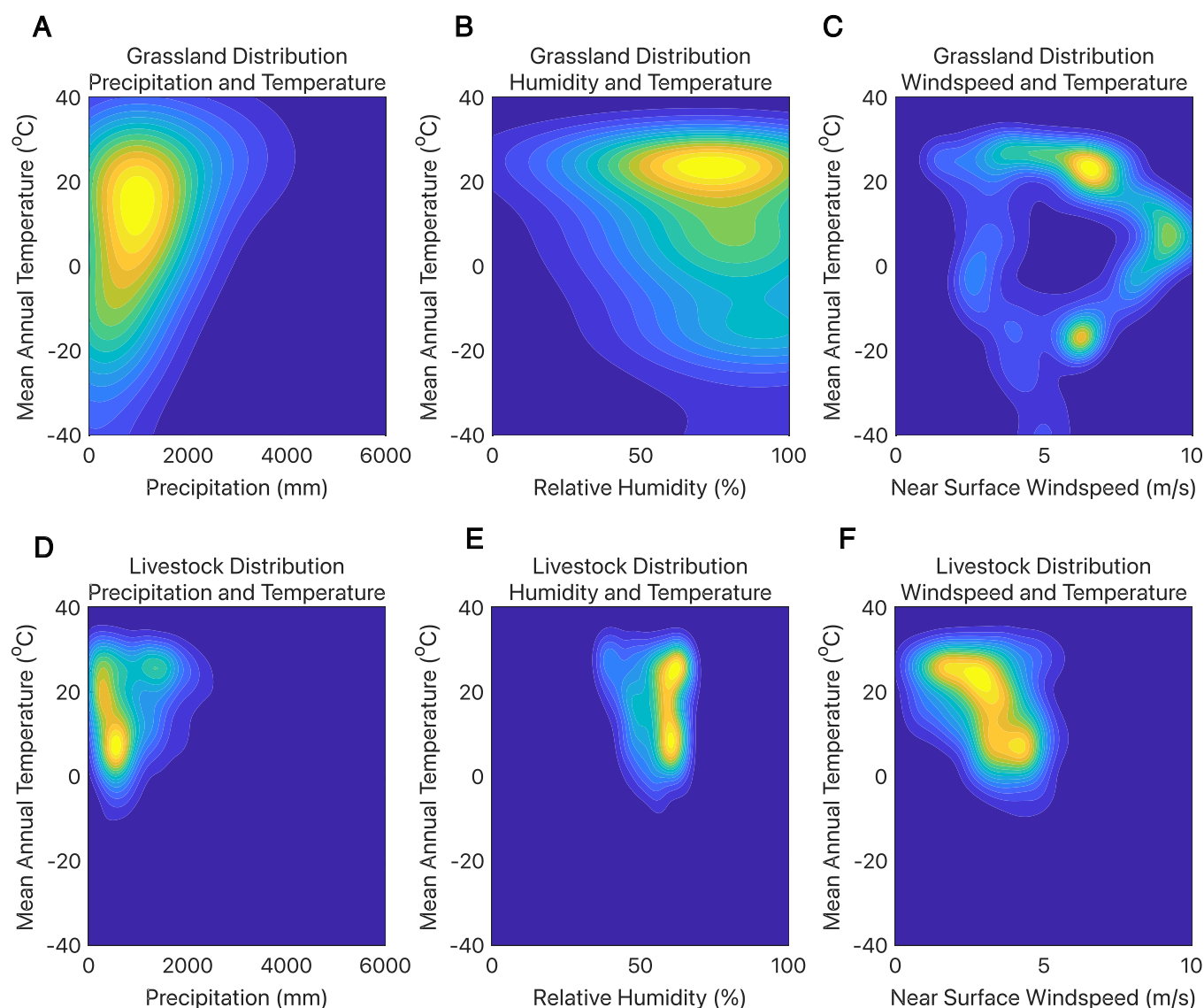
considered in prior work, this is of high importance given that grazing systems are highly sensitive to climate change and home to some of the world's poorest populations (27–29). By integrating climate exposure of grazing systems with socioeconomic vulnerability, our study offers a globally consistent yet regionally differentiated perspective on climate risks to grazing systems. These findings have direct relevance for both adaptation policy and global food system resilience.

## Results

**Safe Climatic Space for Grazing.** We combine data on the present distribution of livestock (cattle, goats and sheep, hereon referred to as livestock) and climate conditions to construct a multidimensional space (refers to the environmental space formed by multiple selected predictor variables, where each variable represents one dimension) within which the suitable conditions for grazing can be identified. We utilize climate datasets from Climatology at High Resolution for the Earth's Land Surface Areas (CHELSA) and multiensemble of Coupled Model Intercomparison Project

(CMIP) models, coupled with livestock distribution datasets from the Gridded Livestock of the World (GLW) database. We included core climatic drivers of grazing suitability, including temperature, precipitation, humidity, and wind speed, for which substantial evidence has been suggested to impact livestock distribution, supported by further empirical evidence (11–14) from the field level and niche modeling literature (30, 31).

Grassland spans extensive parts of the temperature, precipitation, humidity, and wind speed gradients, from the warmest to the coldest, driest to the wettest, and calmest to the windiest regions (Fig. 1 A–C). By contrast, global grazing activities are clustered in a subset of the world's grasslands, enveloped by certain favorable climate conditions (Fig. 1 D–F). Climatic conditions in grasslands can range from a mean annual temperature of  $-40$  to  $35$  °C, precipitation from 5 to 8,000 mm/y, relative humidity from 10 to 100%, and near-surface wind speed from 0 to 10 m/s. By contrast, livestock are not suited to such diverse gradients of climatic conditions and are concentrated in regions with much thinner climate ranges (Fig. 1 D–F). Presently, 95% of grazing occurs within climatic conditions characterized by a mean annual



**Fig. 1.** The distribution of the safe climatic space for grazing. (A–F) shows the distribution of grassland (A–C) and grazing activities (D–F) across climate conditions. Present (D–F) grazing activities are clustered in a subset of the world's grasslands (A–C), enveloped by climate conditions of mean annual temperature, precipitation, humidity, and wind speed. The highlighted yellow regions indicate a high density of livestock/pasture pixel agglomeration and identify regions where grazing is densely distributed, which is a signal of high grazing suitability.

temperature ranging from  $-3$  to  $29$  °C (lower and upper threshold uncertainty:  $-7$  °C to  $4$  °C,  $27$  °C to  $30$  °C), yearly precipitation between 50 and 2,627 mm/y (uncertainty: 11 to 320 mm/y, 2,300 to 3,500 mm/y), relative humidity ranging from 39 to 67% (uncertainty: 30 to 47%, 60 to 87%), and surface wind speeds between 1 and 6 m/s (uncertainty: 0.5 to 1.5 m/s, 5 to 6.5 m/s) (Fig. 1 D–F). These conditions envelop the livestock distribution inside a safe climatic space for grazing (SCS), in which climatic conditions have been suitable to support grazing livestock. As with the distribution of human populations (1, 2), we show that the concentration of livestock can be conceptualized as existing within a multidimensional abstract space defined by climate variables critical to their fitness. Despite being distributed across vast geographic areas on every continent, their distribution, like that of all species and biomes, follows a distinct climate pattern.

We also explored the degree of variation in climate suitability among three prominent types of livestock, i.e., cattle, sheep, and goats (SI Appendix, Fig. S1 A–I). Other domesticated species such as camels, yaks, and buffalos were not included due to the lack of globally consistent distribution data and because their physiological tolerances differ substantially from those of common grazing species. We note that these species occupy environmentally extreme regions (e.g., deserts and high-altitude steppes) and warrant dedicated analysis as more comprehensive datasets become available. We find that climatic constraints for cattle, sheep, and goats do not exhibit fundamental differences, with small variations in the distribution pattern in precipitation and temperature, likely due to slight variations in thermal and drought tolerances. For example, temperature thresholds for sheep and goats are  $-4$  to  $30$  °C and thresholds for cattle are  $-1$  to  $29$  °C. Cattle are distributed in precipitation conditions ranging from 134 to 2,799 mm/y, while sheep and goats are present across slightly lower precipitation gradients, ranging from 11 to 2,799 mm/y. Other climate variables remain highly consistent for all species. Our results corroborate existing research that goats and sheep are more heat/cold/aridity tolerant than cattle. Nevertheless, these results show that the differences in physiology within the common livestock types do not result in fundamental variations in their distribution within the climate envelope space. Climatic constraint thresholds for our main analysis are thus for all livestock, with results of species-specific thresholds and reanalysis in SI Appendix, Figs. S1 and S5 and Texts S1 and S2.

### Global Redistribution of Grazing Suitability under Climate Change.

Our analysis reveals a significant decline in grazing suitability at a continental scale across all RCP scenarios (Fig. 2 and SI Appendix, Table S1). The net turnover of SCS will amount to  $-36$  to  $-50\%$  of the current area by 2100, indicating that around one-third to half of the present SCS areas will be lost due to climate change at the end of the century. Specifically, 59 to 66% of grasslands currently within the SCS will be negatively impacted and fall outside the SCS, while an additional 16 to 23% of new SCS areas are expected to emerge. Notably, continents such as Oceania, Europe, Africa, and South America are expected to experience pronounced net negative turnover in grazing suitability ( $-37$  to  $-66\%$ ,  $-87$  to  $-95\%$ ,  $-16$  to  $-65\%$ , and  $-34$  to  $-50\%$ , respectively), where the contraction of SCS far exceeds any potential expansion (Fig. 2 A–L and SI Appendix, Fig. S5). This trend strongly suggests an overall decline in grazing suitability across these regions.

In Africa, the SCS is projected to migrate south, i.e., restricted to 25 to 35°S latitudes of its current grassland extent (Fig. 2K). Critical grassland regions, including the Sahel, Ethiopian Highlands, East African Rift Valley, Kalahari Basin, and Congo Basin—currently home to a substantial proportion of Africa's livestock—will face a mean annual temperature rising to above

approximately 35 °C in 2100 under RCP8.5 scenario, and will therefore likely fall outside the SCS, thus posing severe challenges to grazing-dependent systems (Fig. 2K). These intercontinental shifts indicate large-scale, cross-continental contractions in grazing suitability.

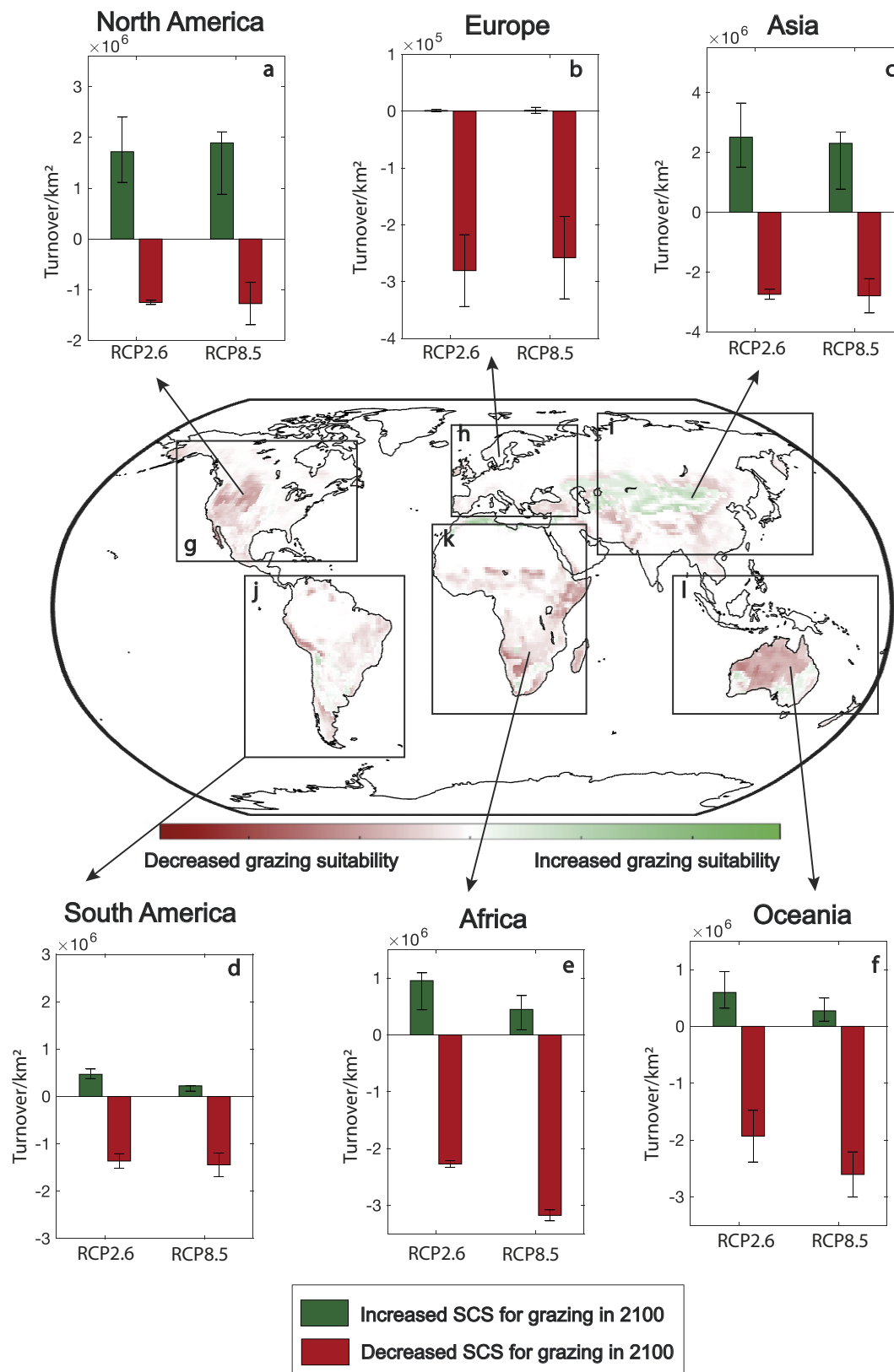
Our findings indicate that these changes in Africa are primarily driven by the southward shift and contraction of SCS by reducing suitable thermal zones. Large areas in Africa are already approaching the upper thermal limit of 29 °C for grazing systems. By 2100, mean annual temperatures in extensive regions will rise to a level that exceeds the temperature thresholds for all common livestock species. This suggests that climate change may impact Africa's grazing systems to such a degree that even changes in herd composition among common livestock species may prove inadequate as an adaptive strategy. While goats and sheep—often referred to as “the poor man's cattle”—have traditionally provided resilience in less favorable climatic conditions characterized by low biomass, aridity, or extreme temperatures, our analysis shows that the severity of future climate change could undermine traditional species-substitution practices, thus reducing the grazing suitability in critical grasslands where livestock currently graze.

The pattern of SCS shift and its underlying mechanism in South America mirrors that observed in Africa, with a predicted decline and southward migration of grazing suitability. As a result, regions between  $\sim 10^{\circ}\text{S}$  and  $20^{\circ}\text{S}$  are expected almost entirely to fall outside the SCS. At the same time, the southernmost areas ( $40^{\circ}\text{S}$  to  $45^{\circ}\text{S}$ ) are projected to become enveloped inside the SCS (Fig. 2J). This shift indicates a decrease in grazing suitability across mid to lower latitudes in South America, accompanied by an increase in suitability in higher latitudes.

In Asia, grazing suitability is projected to expand inland, shifting from its current concentration in the eastern plains to a more westward distribution across the highlands (Fig. 2I), reflecting within-continent redistributions of suitable grazing climates. Future SCS zones are expected to cluster in countries such as Kazakhstan and Iran, encompassing regions like the Central Asian Steppes, Altai Mountains, Tian Shan Range, Mongolian Grasslands, and Northern China Plains. An opposite trend is observed in Oceania, in which a coastal-shift is projected. Central Australian Plains are suggested to exhibit characteristics of high temperature and low humidity, excluding most inland regions outside the SCS.

These results further imply that the scale and degree of future climate change could render traditional adaptive pastoral migration strategies ineffective. While the intracontinental shift of grazing suitability in continents such as Asia may offer opportunities to relocate or migration within the continent, an intercontinental net loss of SCS may pose significant challenges for grazing systems, which are inherently land-based and face constraints on migration on a cross-continental scale (e.g., from Africa to Asia). In contrast, mobile species such as birds or marine fish can respond more flexibly to temperature changes, many of which have been documented to follow isothermal migration patterns across large distances in the ocean or sky without being restricted by continental boundaries. Grazing livestock are also herded by humans and are thus further restricted by political boundaries and associated regulations on top of continental boundaries. A widespread decline in suitability across an entire continent implies limited opportunities for herders to adapt through migration, potentially leading to a loss of subsistence means for substantial populations across multiple countries at a continental scale.

We conducted additional analyses to assess whether a regional-scale approach would alter the key findings of this study. Although cattle, sheep, and goats are unlikely to exhibit fundamental physiological differences across continents—supporting



**Fig. 2.** Continental shift of safe climatic space for grazing. The central map shows the change in grazing areas in climate suitability for grazing (hereafter referred to as grazing suitability) due to climate change, panels (A–L) show regional details. The extensive red shading over Africa (indicating decreases) and green shading over parts of Asia (indicating increases). These opposing trends across continents illustrate the spatial redistribution of grazing suitability with losses and gains. Bar charts show values under emission scenario based on RCP2.6 and RCP8.5, central map shows results for RCP8.5. *Inset* plots show the turnover of land within each continent, in terms of the area of previously suitable land which will become unsuitable (shown in red) and the area of previously unsuitable land which will become suitable (shown in green). Shadings indicate the percentage of the pixel area covered by grassland (0 to 100%). Uncertainty bars in the *Inset* panels reflect uncertainty from using the widest thresholds and thinnest thresholds obtained through all uncertainty analysis, including taking a regional threshold and species-specific threshold, alternate model parameter settings, and using alternate climate datasets (*Methods* and *SI Appendix, Text S1*).

the validity of a globally defined climate space—it remains possible that regional adaptation or management practices shape localized suitability. To account for this, we performed a supplementary reanalysis in which SCS were defined separately for each continent, prior to applying future climate projections (*SI Appendix, Fig. S4 and Text S1*). This allows us to test whether global patterns are robust to region-specific SCS definitions. Further analysis defining SCS at the continental scale yields very similar results regarding the extent of exposure of grazing systems to future climate change (*Methods and SI Appendix, Fig. S4 and Text S1*). While continental-level thresholds are narrower than the global threshold—providing a more nuanced representation of regional heterogeneity—the main findings and conclusions remain robust.

**Socioeconomic Effects of Shifting Grazing Suitability.** This shift of grazing suitability will have global implications for the grazing community, in terms of both population and livestock. To map the implications of climate change and changing suitability on populations and livestock, we quantify the number of negatively impacted populations and livestock (specifically the subset of people who rely on grassland-based grazing rather than industrial livestock systems), and couple with socioeconomic data on social equality, political stability, and economic development indicators, and investigate the collision of impacts with socioeconomically highly vulnerable regions. We analyze the extent of the impact of the SCS shift by corresponding the SCS with the distribution of future projections of pastoral population and livestock, mapped against socioeconomic indicators including the Fragile States Index (FSI), Global Hunger Index (GHI), Gender Inequality Index (GII), and World Development Index (WDI), which are some of the most prominent/representative facets of niche changes (*Methods*).

We show that the future impact of climate change on grazing systems will have an extremely unequal burden on populations. These inequalities span social, economic, and political spheres, with severe-hunger countries, politically unstable countries, high gender inequality countries, and poverty countries burdening most of the impacts.

In 2100, the global population will rise to 12 billion under the business-as-usual scenario (SSP2). Approximately 160 million populations will be residing in grassland-based livestock systems, hereafter referred to as pastoralists, defined by FAO, as residing in high grassland coverage (over 50%), low population density (<20 ppsk), and occurrence of grassland-based livestock (*Methods*). Our estimate is within the range of the estimates from FAO that there are currently 22 to 500 million pastoralists (32, 33). Of these 160 million populations, around 80% of which, or 130 million (110 to 142 million) are expected to be negatively impacted. The tree map in Fig. 3 shows the distribution of negatively impacted populations in countries by income levels, hunger levels, gender inequality levels, and political fragility levels.

We show that 85% of these negatively impacted populations reside in middle to low-income countries (World Bank Development Index), 71% in medium to very high-gender inequality countries (United Nations Gender Inequality Index), 87% in warning to high-alert fragile states countries (Fund for Peace Fragile States Index), and 51% in serious, alarming, and extremely alarming-hunger countries (Welthungerhilfe GHI) (*Methods*). For example, out of the ~130 million people are projected to be negatively affected, ~39% of the population are currently in countries with “Serious Hunger” (e.g., Afghanistan, Kenya, Ethiopia), ~7% in “Extremely alarming Hunger” (e.g., Somali, Yemen), ~5% in “Alarming Hunger” (e.g., Chad, South Sudan), and so forth. This implies that climate change has the potential to impact grazing systems and subsequently induce profound, large-scale, and

rippling impacts across diverse countries, but most strongly in those which are vulnerable in terms of their socioeconomic and political contexts.

Our findings indicate that the global impacts of climate change on grazing systems will disproportionately affect vulnerable groups, with severely influenced countries almost dominating the lowest spectrum in each index. Grazing systems range from pasture systems serving as part of the high-end of meat industry in high-income countries, to the lower end of the socioeconomic spectrum, where pastoralists are often subsistence farmers who rely entirely on grazing for their livelihoods (34, 35).

Although projecting future livestock growth is challenging, if the future growth trend of livestock mirrors that of population growth under a business-as-usual scenario, we estimate that approximately 1.6 billion livestock (1.4 to 1.7 billion) will be negatively impacted. The distribution of these livestock mirrors well with affected populations, with negatively impacted livestock distributed mainly in low- and middle-income countries in Africa and the American continent (*SI Appendix, Fig. S3*).

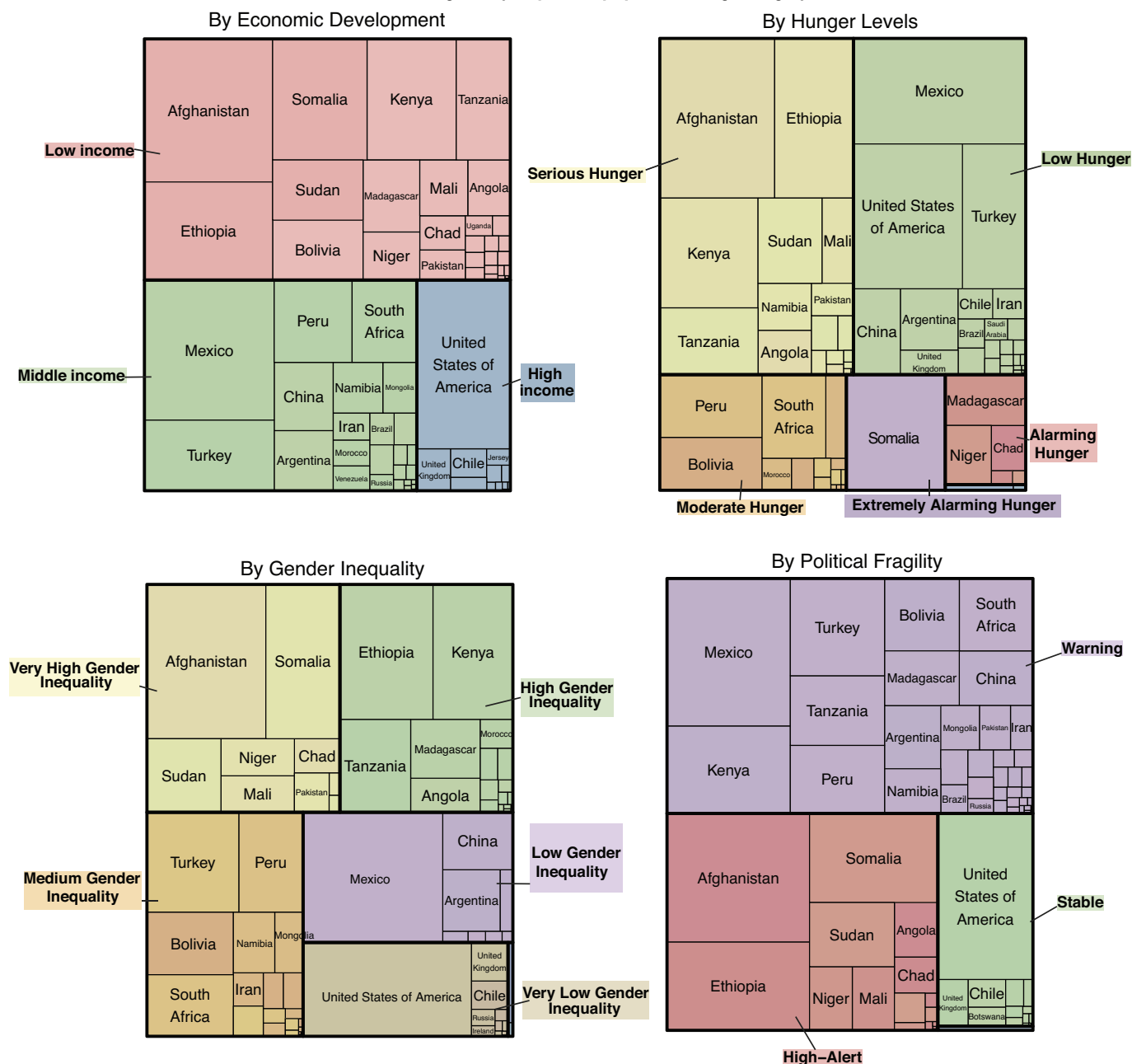
## Discussion

Understanding the impact of climate change on grazing systems is of profound environmental, social, and economic importance, as these systems serve as vital intersections of ecosystem functionality and human welfare. Our analysis finds that the historical distribution of livestock is concentrated within a subset of the available grassland, defined by a multidimensional set of suitable climate conditions. We find that future climate change will induce widespread shifts in the lands which are suitable for livestock, including substantial declines in grazing suitability across entire continents.

These results highlight the magnitude of challenges which pastoral communities may face under future climate change. Moreover, the continental scale of these effects may render traditional coping strategies of migration and species substitution ineffective. While pastoralists have always migrated with the climate, we show that future climate change may lead to a widespread decline in suitability across an entire continent. These results suggest that the scale of future climate change could undermine traditional adaptive pastoral migration, since intercontinental net losses of grazing SCS leave few relocation options for inherently land-bound systems. Unlike mobile species such as birds or fish that can track shifting isotherms across boundaries, herders face limited opportunities when suitability declines across entire continents, threatening subsistence for large populations. We further show that the impact may reach such a degree that even using heat-resilient species such as goats may prove inadequate, as future climates in large regions such as Africa will exceed the upper-temperature threshold (29 to 30 °C) for all common grazing species (cattle, goat, and sheep). This suggests that the biophysical limits of grazing-based livelihoods may be exceeded in many places, limiting the effectiveness of species substitution as an adaptation strategy.

These results challenge the assumption that pastoralists have their own, natural way of responding to environmental change and are thus capable of self-adapting, as they have always done in the past. Given the pressing and unprecedented predicted challenges imposed by climate change, pastoralists should no longer be left to confront these challenges entirely on their own. Policy responses should directly target the structural risks revealed by our projections. Measures such as climate-adaptive pasture restoration, targeted provision of drought-resistant fodder, and livelihood diversification may provide localized benefits but are unlikely to offset systemic continental-scale losses. Social protection programs,

### Distribution of negatively impacted population in grazing systems



**Fig. 3.** Unequal impacts of the shift of grazing suitability on populations globally. We present the distribution of negatively impacted populations in countries by income levels, hunger levels, gender inequality levels, and political fragility levels. The severity is determined by the number of impacted populations in each country. Size and colors indicate the number of impacted populations (in a million units). The darkest shading represents the largest populations (and thus the greatest impacts), whereas the lightest shading indicates the smallest populations (and therefore the smallest impacts). We show that 85% of these impacted populations reside in middle to low-income countries, 71% in medium to very high-gender inequality countries, 87% in warning to high-alert fragile states countries, and 51% in serious-, alarming-, and extremely alarming-hunger countries.

expansion of early warning systems, and planned transition support will be essential to buffer communities whose grazing spaces are projected to contract or disappear.

Furthermore, we show that the impact of climate change on grazing is distributed highly heterogeneously across Earth, both within and between continents, and across socioeconomic gradients. These impacts are particularly alarming as these regions coincide with countries inhabited by communities for whom grazing can be a critical means of subsistence. A decline in grazing suitability in these regions, where pastoralism also has deep historical and cultural significance, at the same time serving as a critical means of land stewardship and subsistence, may induce systemic

outcomes across environmental, social, economic, and even political spheres. For example, a shift out of the SCS in regions such as Chad may reduce grazing suitability, thereby exacerbating already severe hunger rates, heightening political fragility, constraining economic growth, and triggering compounding ecological effects such as biodiversity loss and land degradation. Inability to adapt in time in these impacted regions may cause rippling effects and undermine global sustainability progress across multiple SDGs, such as hunger eradication, food security, promoting social welfare, and alleviating poverty, among others.

The outcomes of this study should raise urgent concerns for the future of global grazing systems. Our projections show that grazing

suitability will decline across entire continents, suggesting that adaptation policies can no longer be designed solely within national boundaries. Because climate change respects neither borders nor local governance structures, grazing management and pastoral risk mitigation will increasingly require coordinated, intergovernmental action. While measures such as subsidies or facilitated mobility have been proposed (36, 37), our findings indicate that these approaches may offer only limited relief where climatic thresholds for grazing are broadly exceeded. While they may enhance resilience in some regions, these measures are unlikely to counteract the systemic, continental-scale contraction of suitable grazing climates we project. Such measures can shift local vulnerability thresholds, but they cannot fully compensate for the widespread biophysical limits imposed by future warming.

Together, these results imply that adaptation efforts must extend beyond incremental or farm-level responses. Instead, adaptation strategies will need to shift from supporting mobility within pastoral systems to facilitating broader livelihood resilience where climatic thresholds for grazing are exceeded. Strategic international planning, climate-informed livestock system transitions, and robust social protection frameworks to support communities are needed in regions where grazing SCS are projected to diminish or disappear.

These conclusions add depth to the ongoing discussion that the populations most vulnerable to climate change are almost precisely the ones who will suffer the greatest impacts. This research also highlights the importance of factoring climate change into discussions around grazing systems management (37), and vice versa, factoring the grazing communities into discussion about impacts of climate change (38). Both connections have been weak in the past and have been understudied, despite the grazing system's high vulnerability and importance in the climate change discourse (39).

This study further confirms and extends the conclusions from previous studies on the human niche (1, 2), suggesting that climate change will put 2 billion populations outside of the climate niche for humans. We further show how climate change will more specifically impact billions of livestock and consequently 110 to 140 million vulnerable populations that depend on them. Similar to other approach (1, 2), our methods have the advantage of mapping out the implications of multidimensional climate change on a global scale which has previously not been revealed. However, we note a few methodological limitations which should be borne in mind. First, we consider only the climate conditions suitable for typically herded livestock (cattle, goats and sheep) and do not consider rarer breeds or unherded natural species. Consequently, regions moving outside of SCS should be interpreted as a signal of decreasing grazing suitability and should not be interpreted as a prediction of inability to graze. Certain rarer breeds of livestock can survive under harsher conditions, and all livestock could theoretically survive on the majority of lands on Earth given the substantial aid of external feed, temperature regulating devices, shelters, etc. Moving out of the SCS is therefore a signal that either pastoralists may have to migrate, or increasing likelihood of reliance on external aids in order to graze. However, although adaptation to climate change is technically always possible, this might be more difficult for grazing systems, as by definition and nature they are not heavily reliant on technological aids. Potential adaptation strategies for grassland-based grazing livestock systems could be considered areas for future research. Without such adaptations, our results imply that climate change will threaten the loss of grazing suitability across large portions of Earth, threatening the livelihoods and cultural heritage of many communities.

Second, our analysis focuses on using a global SCS for grazing to evaluate upper and lower limits to suitability across all systems, but systems may exhibit heterogeneous suitability limits across different

regions due to different local practices and adaptations. Nevertheless, further analysis defining SCS at the continental scale yields very similar results regarding the extent of exposure of grazing systems to future climate change. While continental-level thresholds are narrower than the global threshold—reflecting a more nuanced representation of regional heterogeneity—the main findings and conclusions remain robust (*Methods* and *SI Appendix*, Fig. S4 and Text S1).

We also acknowledge that while our analysis isolates the climatic dimension of grazing viability, it is important to recognize that grazing systems are shaped by a broader set of abiotic and biotic drivers. Soil characteristics—including nutrient availability, texture, and water-holding capacity—strongly influence pasture productivity and can either amplify or buffer climatic stressors. Likewise, predator distributions, wildlife–livestock conflict, and herbivore competition can alter grazing pressure and affect the sustainability of rangeland use. Although these factors fall outside the scope of the safe climate space framework, they interact with climate in ways that may intensify or moderate future risks. Integrating soil, land-use, and ecological constraints into future analyses would provide a more comprehensive assessment of grazing vulnerability and help identify where climatic risks coincide with other systemic pressures.

As the impact of climate change hits ecosystems and communities worldwide, humans and animals must adapt, tolerate, or relocate in accordance with the changing environment or face morbidity or even extinction. Our research presents a complementary perspective to the existing research which has focused on the examination of plant species composition, soil properties, and animal physiology to understand individual components of the impact of climate change on grazing systems. As grazing systems are critical intersections of climate, livestock, ecosystem, and human welfare, we provide a holistic exploration of the connections between climate change, livestock grazing, and socioeconomic outcomes. Through these analyses, we hope to offer a renewed perspective on an enduring, yet increasingly precarious, form of human subsistence and its role within the global climate discourse.

## Methods

**Climate Data.** Present climate data were obtained from downscaled high-resolution sources from CHLSA v2 dataset (40), hosted by the Swiss Federal Institute for Forest, Snow and Landscape Research WSL. This dataset provides climate data at a high resolution (30 arc s, ~1 km). A standard bilinear interpolation method was applied to harmonize the analysis to a 10 km × 10 km resolution. The temporal resolution and time span of the present climate data are in alignment with the grazing data (2010 and 2020). Nine-year decadal averages (2010–2018) were taken for the analysis. Future changes of climate conditions in the year 2100 under the projections of three CMIP climate models, including MIROC-ESM-CHEM r11i1p1, MRI-CGCM3 r11i1p1, and MIROC-ESM r11i1p1, obtained from CMIP model simulations from the Earth System Grid Federation (ESGF) (41). These models provided the full set of variables needed for our analysis (precipitation, relative humidity, temperature, and near surface wind speed) and offer consistent coverage across the historical and projected periods under the RCP scenarios we considered, enabling comparability and robust projection assessment.

**Livestock Distribution Data.** Global livestock distribution was assessed utilizing data from the Food and Agriculture Organization (FAO), specifically the GLW (version 3 and 4) database (42, 43). This database provides harmonized subnational livestock distribution data encompassing various species—cattle, buffaloes, horses, sheep, goats, pigs, chickens, and ducks—at a spatial resolution of 0.083333 decimal degrees for the years 2010 and 2020. In this study, we adopt the common grazing livestock types of cattle, goats, and sheep.

Other domesticated species such as camels, yaks, and buffalos were not included due to the lack of globally consistent distribution data and because their physiological tolerances differ substantially from those of common grazing

species. We note that these species occupy environmentally extreme regions (e.g., deserts and high-altitude steppes) and warrant dedicated analysis as more comprehensive datasets become available. We do not include chickens, ducks, or pigs in our analysis as they are not grazing ruminants and are not raised on grasslands on a large scale.

The system boundary of this study is grassland-based (pastoral) livestock systems, excluding industrial, periurban, and mixed crop-livestock systems. To identify these systems, the GLW livestock layers were filtered using the FAO Global Livestock Production Systems (GLPS) framework. Following FAO definitions, we applied two spatial criteria: 1) Rangeland land-cover classes (GLPS categories dominated by natural grasslands, shrublands, or sparse vegetation), and 2) Population density <20 persons per km<sup>2</sup>, which distinguishes extensive pastoral areas from intensive, urban, or mixed agricultural systems. Only grid cells satisfying both criteria were retained as grassland-based grazing systems. This filtering isolates pastoralist livestock distributions—i.e., populations dependent on natural forage and therefore directly exposed to climatic conditions. Explicitly focusing the scope of our analysis on grassland-based grazing systems can ensure that the studied system is closely dependent on natural systems, whereby animals rely directly on natural resource availability, climatic conditions for forage, water, etc., thus largely excluding bias from other systems, such as industrial feedlots.

Grassland cover data were obtained from the Earth Env dataset supported by NCEAS, NASA, NSF, and Yale University. This dataset provides information on twelve land cover types per grid at a spatial resolution of 1 km (44). Future grassland data to 2100 were sourced from the Harmonized Global Land Use dataset (LUH2), providing fractional land use and land cover patterns for the globe at 0.5-degree spatial resolution for 2015–2300 under various RCP scenarios. This output forms a consistent, spatially detailed set of land-use change scenarios essential for studying human impacts on the Earth system. For additional information on the methodologies, inputs, and options behind the future land use transitions data, see Ma et al. (45), Hurtt et al. (46), and Chini et al. (47). Future population estimations under business-as-usual scenarios are from the Global 1-km Downscaled Population Base Year and Projection Grids Based on the Shared Socioeconomic Pathways obtained from EARTHDATA (48).

**Safe Climatic Space for Grazing.** To characterize the climatic space, we initially considered five bioclimatic variables including temperature, precipitation, humidity, wind speed, and radiation for which substantial evidence has been suggested to impact livestock distribution, supported by further empirical evidence (11–14) from the field level and niche modeling literature (30, 31). To summarize, these studies found that near-surface air temperature (tas), precipitation (pr), near-surface wind area (sfcWind), and relative humidity (hurs) are crucial determinants of physiological performance, water and forage availability, pathogen dissemination, and ultimately the distribution and productivity of livestock (21, 30–32, 49). Assessments of temperature and humidity were motivated by demonstrated impacts on heat stress and cold tolerance, or the range of ambient temperatures and humidity within which an animal can maintain normal physiological function, health, and productivity without experiencing heat or cold stress. Assessments of precipitation were motivated by impacts on water and forage availability, assessments of wind speed were motivated by established impacts on thermic comfort for heat dissipation and affecting apparent temperature, as well as pathogen dissemination. Large empirical evidence has shown that variations beyond the adaptive capacity of these factors can lead to impaired growth, reduced reproduction, and disease resistance, potentially causing illness and death (11, 12).

We first filtered variables based on their biological relevance to medium to large ruminant livestock physiology and life history. To avoid model overfitting and issues arising from multicollinearity, we assessed correlations among the remaining candidate variables. We calculated partial Pearson's correlation coefficients and Variance Inflation Factors (VIF) for all pairs of predictors extracted from the occurrence locations. We applied a correlation threshold of >|0.7|. For any highly correlated pair, we retained the variable that was arguably more proximal to the species' ecology or showed higher permutation importance in preliminary model runs. This resulted in a final set of four independent environmental predictors used for model calibration, for which all VIF scores are below 2 (SI Appendix, Tables S3 and S4).

We then used a four-dimensional threshold method (1, 2, 50) to delineate the distribution of our climatic variables by discerning the prevailing patterns of four climatic variables where livestock grazing predominantly occurs. Following

methods by refs. 1, 25, 26, and 51, we defined our SCS by setting thresholds encompassing the central 95th percentile of the climate conditions (51–54) associated with grazing activities. This approach excludes the marginal extremes where grazing is performed under atypical conditions by specialized breeds, envelopes all grazing distribution and excludes 5% outliers. We also test for the influence of excluding 1% outliers and 10% outliers, which shows that the impact of outlier setting on thresholds does not have a significant impact on the main results (SI Appendix, Text S1).

**Future Climate Impacts on Grazing Systems.** Future suitable grazing areas are those areas which are grassland and also encompass the SCS. The present SCS is mapped with the future changes in climate conditions in the year 2100 under the multiensemble CMIP models (Methods and SI Appendix, Text S1). Future changes of climate conditions in the year 2100 under the projections of three CMIP climate models, including MIROC-ESM-CHEM r1i1p1, MRI-CGCM3 r1i1p1, and MIROC-ESM r1i1p1, obtained from CMIP model simulations from the ESGF (41). Future grassland data to 2100 were sourced from the Harmonized Global Land Use dataset (LUH2), providing fractional land use and land cover patterns for the globe for 2015–2300 under various RCP scenarios.

**Socioeconomic Analysis.** Grid-level data from the previous analysis were aggregated to the country level, which were then mapped with a range of socioeconomic indexes including the FSI, GII, GHI, and economic development index. FSI data, compiled by the Fund for Peace, rank countries based on vulnerability using 12 indicators across social, economic, and political dimensions, with scores grouped into three categories: High Alert, Warning, and Stable. GII, developed by UNDP, assesses gender disparities across reproductive health, empowerment, and labor market participation, categorizing countries into High, Moderate, and Low Gender Inequality. GHI, published by Concern Worldwide and Welthungerhilfe, measures undernutrition through four indicators, ranking countries into Low, Moderate, and High Hunger categories. World Bank income classifications categorize countries into Low-Income (GNI per capita ≤ \$1,145), Middle-Income (\$1,146–\$13,845), and High-Income (≥\$13,846) groups, updated annually for global economic trends. These indices provide a framework for analyzing global inequality, vulnerability, and development (SI Appendix, Text S3).

Population data are obtained from Gridded Population of the World, Version 4 (GPWv4). This dataset models the distribution of human population (counts and densities) on a continuous global raster surface. We utilize the dataset at a resolution of 2.5 min (~5 km at the equator). Future population data are obtained from Global 1-km Downscaled Population Base Year and Projection Grids Based on the Shared Socioeconomic Pathways obtained from EARTHDATA. In this study, we used SSP5–8.5, which corresponds to RCP8.5, and SSP1–2.6, which corresponds to RCP2.6.

**Sensitivity Analysis.** We conducted accuracy assessments by investigating the structural and parametric uncertainties of the SCS and datasets (see also SI Appendix, Figs. S2–S9 and Texts S1 and S2). To target uncertainties associated with model settings and input datasets, we conduct a sensitivity analysis and reanalysis by taking a regional threshold approach, alternate model parameter settings, and using alternate datasets.

We first investigate the parametric uncertainties of our results. Here, parametric uncertainties refer to the model setting of taking thresholds as the central 95th percentile of the livestock distribution. This method eliminates the outliers in species distribution datasets and is commonly used in climate niche analysis (51–54). Nevertheless, uncertainties can emerge from this choice. We account for parametric uncertainties by considering alternate percentiles of 99th and 90th, and conduct reanalysis through adopting these thresholds.

Uncertainties may also arise from climate datasets. To account for the uncertainty within climate datasets, we first use multiensemble for each accounting period in which CMIP models are used. We then conduct reanalysis of the present niche by replacing the CHELSA climate dataset by CMIP climate datasets used for historical and future climate analysis, so as to reduce systemic differences in variations in different climate observations/projections datasets.

We then investigate the structural uncertainties associated with SCS modeling. In the main analysis, we used a global climate as the data input to determine a globally consistent niche range, which majority of climate niche modeling studies adopt, under the assumption that species globally do not exhibit fundamental differences. However, there is also the possibility that livestock suitability can

be different on different continents, as they may evolve to become region-specific. We therefore perform additional reanalysis of the future of the SCS shift in which SCS are defined at continental scales as opposed to global scales prior to consideration of future climate change projections (*SI Appendix, Fig. S4 and Text S1*). The continental-scale niche reanalysis confirms the robustness of the main results. Despite the fact that the thresholds are narrower for individual continents compared to the global threshold, an adjustment that more accurately captures regional heterogeneity, the main results and conclusions remain unchanged (*Methods and SI Appendix, Fig. S4 and Text S1*).

We also investigate the uncertainties arising from the aggregation of three livestock species. In the main analysis, we focus on the three livestock species for comprehensive capture of common grazing livestock and aggregated the livestock species counts. However, variations may arise from the minor threshold differences between the three livestock types. We thus account for this uncertainty by conducting analysis for species-specific analysis and subsequent reanalysis of our results. Results show that variations within-livestock species do not result in significant variations in future projections of grazing suitability (*SI Appendix, Text S1*).

Taking into account all these uncertainties, we last conduct reanalysis by using the widest thresholds and thinnest thresholds obtained through all of above uncertainty analysis. Results of the range of impacts on the results from the widest and thinnest thresholds are reported in the results and figures in the main text.

1. C. Xu, T. A. Kohler, T. M. Lenton, J.-C. Svenning, M. Scheffer, Future of the human climate niche. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 11350–11355 (2020).
2. T. M. Lenton *et al.*, Quantifying the human cost of global warming. *Nat. Sustain.* **6**, 1237–1247 (2023). 10.1038/s41893-023-01132-6.
3. F. C. Womersley *et al.*, Climate-driven global redistribution of an ocean giant predicts increased threat from shipping. *Nat. Clim. Change* **14**, 1282–1291 (2024). 10.1038/s41558-024-02129-5.
4. C. Li *et al.*, Climate-driven ecological thresholds in China's drylands modulated by grazing. *Nat. Sustain.* **6**, 1363–1372 (2023).
5. F. T. Maestre, Y. L. Bagousse-Pinguet, M. Delgado-Baquerizo, Grazing and ecosystem service delivery in global drylands. *Science* **378**, 915–920 (2022).
6. K.-H. Erb *et al.*, Unexpectedly large impact of forest management and grazing on global vegetation biomass. *Nature* **553**, 73–76 (2018).
7. D. B. Hewins *et al.*, Grazing and climate effects on soil organic carbon concentration and particle-size association in northern grasslands. *Sci. Rep.* **8**, 1336 (2018).
8. K.-H. Erb *et al.*, A comprehensive global 5 min resolution land-use data set for the year 2000 consistent with national census data. *J. Land Use Sci.* **2**, 191–224 (2007).
9. G. P. Asner, A. J. Elmore, L. P. Olander, R. E. Martin, A. T. Harris, Grazing systems, ecosystem responses, and global change. *Annu. Rev. Env. Resour.* **29**, 261–299 (2004).
10. T. Fetzl *et al.*, Quantification of uncertainties in global grazing systems assessment. *Glob. Biogeochem. Cycles* **31**, 1089–1102 (2017).
11. T. L. Mader, L. J. Johnson, J. B. Gaughan, A comprehensive index for assessing environmental stress in animals. *J. Anim. Sci.* **88**, 2153–2165 (2010).
12. U. Bernabucci *et al.*, Metabolic and hormonal acclimation to heat stress in domesticated ruminants. *Animal* **4**, 1167–1183 (2010).
13. S. Li, L. Wang, Q. Song, Y. Wang, Analysis of livestock climate resources in Daxinganling area. *Heilongjiang Meteorol.* **28–29** (2002). 10.14021/j.cnki.hljqx.2002.04.0091002-252X(2002)04-0028-03.
14. W. P. Blount, *Intensive Livestock Farming* (William Heinemann Medical Books, London, 1968), p. 612.
15. J. Ben Keane *et al.*, Grassland responses to elevated CO<sub>2</sub> determined by plant-microbe competition for phosphorus. *Nat. Geosci.* **16**, 704–709 (2023).
16. Y. Wang *et al.*, Risk to rely on soil carbon sequestration to offset global ruminant emissions. *Nat. Commun.* **14**, 7625 (2023).
17. R. A. Gill *et al.*, Nonlinear grassland responses to past and future atmospheric CO<sub>2</sub>. *Nature* **417**, 279–282 (2002).
18. K. Guan *et al.*, Continental-scale impacts of intra-seasonal rainfall variability on simulated ecosystem responses in Africa. *Biogeosciences* **11**, 6939–6954 (2014).
19. L. L. Sloat *et al.*, Increasing importance of precipitation variability on global livestock grazing lands. *Nat. Clim. Change* **8**, 214–218 (2018).
20. J. M. Craine *et al.*, Timing of climate variability and grassland productivity. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 3401–3405 (2012).
21. V. P. Rashamol *et al.*, Physiological adaptability of livestock to heat stress: An updated review. *J. Anim. Behav. Biometeorol.* **6**, 62–71 (2018).
22. C. Godde *et al.*, Climate change and variability impacts on grazing herds: Insights from a system dynamics approach for semi-arid Australian rangelands. *Glob. Change Biol.* **25**, 3091–3109 (2019).
23. A. Brouillette, B. Sultan, Livestock exposure to future cumulated climate-related stressors in West Africa. *Sci. Rep.* **13**, 2698 (2023).
24. F. Ritter, M. Berkelhammer, C. Garcia-Eidell, Distinct response of gross primary productivity in five terrestrial biomes to precipitation variability. *Commun. Earth Environ.* **1**, 34 (2020).
25. M. Kumm, M. Heino, M. Taka, O. Varis, D. Viviroli, Climate change risks pushing one-third of global food production outside the safe climatic space. *One Earth* **4**, 720–729 (2021).
26. S. Heikonen *et al.*, Climate change threatens crop diversity at low latitudes. *Nat. Food* **6**, 331–342 (2025). 10.1038/s43016-025-01135-w.
27. E. Buisson, S. Archibald, A. Fidelis, K. N. Suding, Ancient grasslands guide ambitious goals in grassland restoration. *Science* **377**, 594–598 (2022).
28. S. DeWitt *et al.*, Seeing the grasslands through the trees. *Science* **351**, 1036–1036 (2016).
29. D. R. Kemp *et al.*, Innovative grassland management systems for environmental and livelihood benefits. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 8369–8374 (2013).
30. W. P. Porter, M. Kearney, Size, shape, and the thermal niche of endotherms. *Proc. Natl. Acad. Sci. U.S.A.* **106**, 19666–19672 (2009).
31. E. A. Riddell *et al.*, Parameterizing mechanistic niche models in biophysical ecology: A review of empirical approaches. *J. Exp. Biol.* **226**, jeb245543 (2023).
32. N. E.-H. Scialabba, "Introduction to livestock systems" in *Managing Healthy Livestock Production and Consumption*, Nadia El-Hage Scialabba, Ed. (Elsevier, 2022), pp. 3–25. 10.1016/B978-0-12-823019-0.00010-6.
33. FAO, Nitrogen inputs to agricultural soils from livestock manure (2018).
34. Food and Agriculture Organization of the United Nations (FAO), *People and Animals: Traditional Livestock Keepers: Guardians of Domestic Animal Diversity* (Food and Agriculture Organization of the United Nations, Rome, 2007).
35. FAO, *World Agriculture: Towards 2015/2030* (Food and Agriculture Organization, Rome, 2003).
36. L. Wang *et al.*, Diversifying livestock promotes multidiversity and multifunctionality in managed grasslands. *Proc. Natl. Acad. Sci. U.S.A.* **116**, 6187–6192 (2019).
37. L. Palmer, A new climate for grazing livestock. *Nat. Clim. Change* **4**, 321–323 (2014).
38. A. A. Golub *et al.*, Global climate policy impacts on livestock, land use, livelihoods, and food security. *Proc. Natl. Acad. Sci. U.S.A.* **110**, 20894–20899 (2013).
39. M. M. Rojas-Downing, A. P. Nejathashemi, T. Harrigan, S. A. Woznicki, Climate change and livestock: Impacts, adaptation, and mitigation. *Clim. Risk Manag.* **16**, 145–163 (2017).
40. D. N. Karger *et al.*, Climatologies at high resolution for the Earth's land surface areas. *Sci. Data* **4**, 1–20 (2017).
41. B. C. O'Neill *et al.*, The scenario model intercomparison project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.* **9**, 3461–3482 (2016).
42. M. Gilbert *et al.*, Global distribution data for cattle, buffaloes, horses, sheep, goats, pigs, chickens and ducks in 2010. *Sci. Data* **5**, 1–11 (2018).
43. T. P. Robinson *et al.*, Mapping the global distribution of livestock. *PLoS One* **9**, e96084 (2014).
44. M.-N. Tuanmu, W. Jetz, A global 1-km consensus land-cover product for biodiversity and ecosystem modelling: Consensus land cover. *Glob. Ecol. Biogeogr.* **23**, 1031–1045 (2014).
45. L. Ma *et al.*, Global rules for translating land-use change (LUH2) to land-cover change for CMIP6 using GLM2. *Geosci. Model Dev.* **13**, 3203–3220 (2020).
46. G. C. Hurtt *et al.*, Harmonization of land-use scenarios for the period 1500–2100: 600 years of global gridded annual land-use transitions, wood harvest, and resulting secondary lands. *Clim. Change* **109**, 117 (2011).
47. L. P. Chini *et al.*, LUH2-GCB2019: Land-use harmonization 2 update for the global carbon budget, 850–2019. *ORNL DAAC* (2021).
48. B. Jones, B. C. O'Neill, J. Gao, *Global 1-km Downscaled Population Base Year and Projection Grids for the Shared Socioeconomic Pathways (SSPs), Revision 01* (NASA Socioeconomic Data and Applications Center (SEDAC), Palisades, NY, 2020). 10.7927/Q729-9R69.
49. R. J. Collier, J. L. Collier, *Environmental Physiology of Livestock* (Wiley-Blackwell, Ames, IA, 2012).
50. R. J. Hijmans, C. H. Graham, The ability of climate envelope models to predict the effect of climate change on species distributions. *Glob. Change Biol.* **12**, 2272–2281 (2006).
51. M. Chevalier, O. Broennimann, A. Guisan, Climate change may reveal currently unavailable parts of species' ecological niches. *Nat. Ecol. Evol.* **8**, 1298–1310 (2024).
52. D. Z. Atwater, C. Ervine, J. N. Barney, Climatic niche shifts are common in introduced plants. *Nat. Ecol. Evol.* **2**, 34–43 (2017).
53. M. A. Carretero, N. Sillero, Evaluating how species niche modelling is affected by partial distributions with an empirical case. *Acta Oecol.* **77**, 207–216 (2016).
54. N. Velasco, N. Andrade, C. Smit, R. Bustamante, Climatic niche convergence through space and time for a potential archaeophyte (*Acacia caven*) in South America. *Sci. Rep.* **13**, 9340 (2023).
55. C. Li, grazing: Code and supplementary data. GitHub. <https://github.com/lichaohui1997/grazing>. Accessed 19 January 2026.

The analysis shows that the main results of our study are robust against alternative climate datasets, niche models, and species-specific thresholds.

**Data, Materials, and Software Availability.** All code used in this study is publicly available in the GitHub repository <https://github.com/lichaohui1997/grazing> (55). All other data are included in the manuscript and/or *SI Appendix*.

**ACKNOWLEDGMENTS.** G.C. acknowledges funding from the National Natural Science Foundation of China (Grant No. 12372379). P.P. acknowledges funding from the European Research Council Starting Grant 2022 for the BEYONDSOG project (grant agreement No 101077492). X.W. acknowledges funding from the Alexander Von Humboldt Fellowship and Marie Skłodowska-Curie Fellowship.

Author affiliations: <sup>a</sup>Potsdam Institute for Climate Impact Research, Member of the Leibniz Association, Potsdam D-14412, Germany; <sup>b</sup>Laboratory of Systems Ecology and Sustainability Science, School of Engineering, Peking University, Beijing 100871, China; <sup>c</sup>Climate Change and Variability Group, Earth Sciences Department, Barcelona Supercomputing Centre, Barcelona 08034, Spain; <sup>d</sup>Integrated Research on Energy, Environment and Society Energy and Sustainability Research Institute Groningen, University of Groningen, Groningen 9747 AG, the Netherlands; <sup>e</sup>School of Soil and Water Conservation, Beijing Forestry University, Beijing 100083, China; <sup>f</sup>School of Ecology, Environment and Resources, Guangdong University of Technology, Guangzhou 510006, China; and <sup>g</sup>Macao Environmental Research Institute, Macau University of Science and Technology, Macao 999078, China