

Perspective

Rangelands as adaptation reserves, not carbon units

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SUMMARY

Climate policy increasingly asks the world's rangelands, which cover roughly half of Earth's land surface and hold nearly a third of global soil organic carbon, to deliver measurable, creditable soil-carbon gains through grazing management. Rangeland adaptation draws on spatial, temporal, and institutional heterogeneity, whereas carbon accounting requires comparable practices or outcomes across operations. Grazing effects on soil carbon vary in direction and magnitude with climate, soils, vegetation, and grazing history. Projected climate-driven soil-carbon losses exceed modeled grazing benefits except in scenarios that assume a widespread compensatory plant-growth response to grazing. Managing rangelands as standardized carbon units can narrow the landscape and institutional heterogeneity that sustains adaptive capacity. We advance the hypothesis that landscape heterogeneity can propagate to the within-soil diversity that supports carbon persistence as conditions change. If so, carbon accounting may weaken the conditions that allow carbon to persist. This conflict is not inherent to grazing but arises when policy is organized around a single commodity. We propose managing rangelands as heterogeneous adaptation reserves through interacting disturbances, flexible technologies, and collaborative networks that preserve the capacity to absorb disturbance and reorganize as conditions change.

INTRODUCTION

"The sustainability of grazed systems is a more fundamental issue than grazing optimization."

—D. Briske ("Grazing Optimization: A Plea for a Balanced Perspective"¹)

Soil carbon has become a new commodity that rangelands are being asked to produce. Rangelands, defined here as lands where native or naturalized vegetation supports or could support extensive grazing, include grasslands, shrublands, savannas, and open woodlands and cover roughly half of Earth's land surface.^{2–4} These lands are inherently variable. Their soils, vegeta-

tion, and disturbance regimes change across space and through time. This variation is critical for how rangelands function, but it complicates attempts to secure stable, measurable outputs. Carbon policy requires gains that can be attributed and verified, whereas rangeland adaptation depends on retaining the capacity to respond to changing local conditions (Box 1). This problem is not unique to rangelands. Wherever climate policy converts a complex ecosystem into a single creditable output, whether forest carbon, blue carbon, or soil carbon in croplands, the same tension can arise between what accounting must standardize and what adaptation requires. Rangelands offer a clear case because their function depends so visibly on variability, but the lessons may extend to other systems governed as carbon commodities.

Box 1. Definitions of key terms

We use *heterogeneity* to mean spatial and temporal variability at three linked scales: within the soil, the diversity of organic compounds, organisms, and microsites; across the landscape, the variation in vegetation structure, disturbance, and forage; and across institutions, the variation in management practices, stocking strategy, decision-making, and governance.

Adaptive capacity is the potential of a social-ecological system to adjust its management, institutions, or ecological functions in response to existing and emerging stressors.^{5,6}

Resilience denotes the capacity of a system to absorb disturbance while maintaining essential functions and the potential to reorganize.^{5,7}

We use *adaptation* in this social-ecological sense.

We distinguish two related meanings of carbon *persistence* here: in the descriptive sense it is the retention of soil organic matter over ecologically relevant timescales, that is, how much carbon stays in the soil rather than being respired or eroded; and in the process sense it is the resistance and resilience of the stabilization pathways themselves, the capacity of the soil environment to keep forming and protecting organic matter as conditions change.

Non-equilibrium dynamics describes system behavior driven by variable, episodic forcing such as fluctuating rainfall and patchy disturbance rather than tracking a single stable state, a property that can also leave rangelands and their soils lagging behind a changing climate for long periods.

Carbon-centric grazing refers to the framing of grazing management primarily to increase or maintain creditable belowground carbon storage, whether adopted by producers, programs, or markets.

This distinction between variation as function and variation as accounting uncertainty matters because rangelands have never been well described as systems moving predictably toward a single stable condition. Their dynamics are shaped by variable rainfall, patchy disturbance, and shifting animal use, and influenced by management decisions made with incomplete information. Rising greenhouse-gas concentrations add another element to this variability. Because of delayed ecosystem responses to rapidly changing climate forcing, terrestrial systems will remain out of equilibrium with climate for millennia,^{8–11} and novel climates and communities are already emerging.^{12,13} Under these conditions, management frameworks built around predictable gains in a single output are poorly matched to the systems they seek to govern.

Despite this mismatch, soil carbon attracts growing policy interest. Rangelands hold roughly 30% of global soil organic carbon,¹⁴ much of it secured simply by remaining uncultivated, since converting these lands to cropland releases a substantial share.¹⁵ Influential assessments nonetheless frame improved grazing management as a scalable natural climate solution.^{16–19} "Carbon-centric grazing" remains uncommon in practice and is rarely the primary aim of producers who adopt related practices.²⁰ Even so, carbon markets, public climate programs, and supply-chain sustainability initiatives increasingly create incentives to translate grazing management into credited carbon outcomes.^{21–24}

Turning this policy interest into credits or payments requires simplification of complex rangeland systems. Carbon credits and payment programs depend on outcomes or practices that

can be monitored and attributed across operations. In practice, this favors management actions that are visible to external auditors and legible to prescribed models and practice standards. Wetland mitigation banking in the United States similarly requires functions lost at one site to be made equivalent to functions produced at another.²⁵ For rangelands, standardization operates through voluntary carbon protocols and project methodologies,^{21,23} government conservation and agricultural payment programs,^{22,24} and global natural climate solution assessments that aggregate diverse systems into common carbon categories.^{17,26} If grazing can increase soil carbon without causing degradation, it appears to offer a scalable, low-cost climate solution. Yet, grazing and soil-carbon studies consistently find that the soil-carbon response is highly variable and difficult to generalize.^{27,28} Policy-relevant assessments and accounting systems, however, must convert that variability into generalized rates, practices, and claims. In doing so, they make carbon look more governable than it is. Even if grazing reliably stored carbon, managing to maximize that single output would sacrifice the variability that adaptation requires.

These two observations, that heterogeneity sustains rangeland function and that managing grazing for soil carbon yields small and unreliable gains, have each been made before but have largely developed in separate literatures. Research on grazing and soil carbon has found that additional rangeland carbon storage is small relative to global emissions.^{29,30} In arid rangelands, measurement and monitoring costs can consume the resulting payments, and carbon policy underweights the non-equilibrium dynamics of these systems.³⁰ Research on heterogeneity spans decades of work on rangeland disturbance, patch dynamics, and non-equilibrium rangeland ecology. Considered together, these two bodies of literature suggest that the heterogeneity adaptation requires may also sustain the persistence of soil carbon, understood here as an emergent property of the soil environment that continuously forms organic matter and resists decomposition. In this view, variability that carbon accounting treats as noise may be the system property that allows carbon to remain in soil. We advance this linkage as a hypothesis. If substantiated with evidence, it would require a rethinking of rangeland carbon policy, because managing rangelands as uniform carbon units may erode the heterogeneity that supports carbon persistence.

Heterogeneity in our usage here spans three interconnected scales (Box 1). Standardization acts on landscape and institutional scales by narrowing disturbance regimes and the range of management responses available under changing conditions.^{31–33} Whether standardization also erodes the within-soil heterogeneity that sustains carbon persistence depends on the hypothesized cross-scale link. The case against single-commodity policy therefore does not require that link to hold, but it is strengthened if it does.

We argue that rangelands should not be managed primarily as carbon units. This does not mean that soil carbon is unimportant or that grazing and carbon storage are necessarily in conflict. At the scale of individual operations, carbon storage, biodiversity, forage production, and livelihoods can often be pursued together. The conflict emerges when policy is organized around a single commodity. We propose managing rangelands as

"heterogeneous adaptation reserves," meaning working and wild rangelands managed to keep variability, disturbance, and a range of response options available. Two elements distinguish our argument from prior calls to favor adaptation over rangeland carbon: a hypothesized cross-scale link from landscape and institutional heterogeneity to the within-soil diversity that confers carbon persistence, and the claim that carbon accounting is self-undermining because it erodes that heterogeneity. We first situate carbon policy within a longer history of homogenized production. We then examine why carbon maximization is a poor organizing principle for adaptation. Its projected gains are small and contingent, climate dynamics overwhelm management effects, and standardization can erode the heterogeneity that adaptation draws on. Alongside this critique, we advance our central hypothesis that heterogeneity retained or regenerated by grazing and other forms of disturbance may sustain the persistence of soil carbon. We end by outlining strategies that treat heterogeneity as the basis for future adaptation.

CARBON POLICY EXTENDS A UNIFORMITY PARADIGM

Efforts to make variable rangelands produce measurable outputs long predate carbon markets. Range science developed partly in response to overgrazing, drought, and the problem of controlling livestock use on variable landscapes.³⁴ Much of the early discipline was organized around sustainable forage production, carrying capacity, and proper use.³⁵ In practice, this often meant reducing uneven grazing by distributing livestock more uniformly in space and time. Later critiques described this tendency as "management to the middle," in which moderate and even use becomes the default objective.^{36–38} This uniformity paradigm reduced some forms of localized degradation and supported livestock production, but it treated spatial variation in disturbance as something to be corrected and ignored how it sustains biodiversity and ecosystem function.

Soil carbon raises the stakes because it links local grazing decisions to global mitigation accounting. Henderson et al.³⁹ modeled grazing management as a global mitigation pathway, noting that practices carry a high risk of increasing soil-based greenhouse gases where applied outside a relatively small effective area and that indicators are needed to identify amenable areas before large-scale implementation. As the estimate moved into successive global assessments, this spatial-targeting condition faded from view. Griscom et al.¹⁷ named grazing optimization as a natural climate solution pathway, a prescription that in its original form varied stocking rate by site condition; Bossio et al.¹⁶ retained it; and Fargione et al.⁴⁰ applied it to the United States as a single national figure, by which point the site differentiation had been reduced to a flat, area-wide rate. The pathway became recognized, and the original spatial-targeting condition—that gains depend on amenable areas and that untargeted application can lose soil carbon—traveled less well. Project-scale crediting protocols arrive at the same end by a separate route. Verra's Improved Agricultural Land Management methodology, the Climate Action Reserve's Soil Enrichment Protocol, and the Emissions Reduction Fund's soil-carbon method^{41–43} operationalize the assumption through their own measurement and modeling. Both lineages descend from the same science.

Syntheses showing that improved grazing management can raise soil carbon^{44,45} were routed through national-inventory accounting^{46,47} into crediting rules. By then the premise is treated less as a finding to be tested and more as a standard to be applied.

In practice, this standard operates through public programs, most clearly in the United States. There, financial and technical assistance to private rangelands has long favored practices meant to even out grazing, chiefly fencing, water development, and brush control, all of which now appear on the United States Department of Agriculture (USDA) Natural Resources Conservation Service's list of climate-mitigation activities.⁴⁸ These are high-cost interventions that carry no metric of heterogeneity at any scale. The same logic reaches private supply chains, where the beef industry's sustainability framework incorporates soil-carbon gains from grazing management into its standardized metrics.⁴⁹ Carbon-centric grazing does not introduce this apparatus so much as add a commodity to it, which is part of why it has been taken up so readily.

CARBON MAXIMIZATION ASSUMES PREDICTABLE, SCALABLE OUTCOMES

Global estimates of grazing mitigation depend on how models represent plant production, spatial targeting, accumulation time, and livestock emissions^{39,50} and remain poorly aligned with observed variability of soil-carbon responses to grazing.^{27,28} Carbon-centric grazing is one of several practices promoted as natural climate solutions.^{16–18} Influential reviews suggest natural climate solutions collectively could provide more than a third of cost-effective mitigation needed by 2030 to keep warming below 2°C.^{17,19} Global management prescriptions generally involve moderate stocking rates and uniform forage offtake, often integrated within rotational systems designed to maximize primary production and carbon inputs to soil.^{28,39,51} A parallel, field-scale literature reinforces this promise, reporting rapid soil-carbon gains under intensive rotational grazing systems and proposing that the timing, intensity, and frequency of defoliation be tuned to maximize sequestration.^{51–53}

Published global estimates of grazing mitigation span more than an order of magnitude, but they measure different outcomes. Henderson et al. estimated 0.15 Gt CO₂equiv year^{−1} from soil carbon, annualized over 20 years on the 28% of simulated grazing land where their model predicted a gain. When additional forage was assumed to increase animal numbers and emissions proportionally, the combined intervention became a net source of 0.57 Gt CO₂equiv year^{−1}.³⁹ Ren et al. estimated 45–81 Pg C of additional carbon in vegetation and soil under optimized grazing but did not estimate how long the increase would take.²⁸ Powell et al. estimated net climate benefits of 0.37 ± 0.22 Gt CO₂equiv year^{−1} under constant plant production with pixel-level feed supplementation to maintain production and 1.83 ± 0.45 Gt CO₂equiv year^{−1} when a grazing-production-response curve was applied across the global model domain and livestock production was maintained at the country level.⁵⁰ The corresponding modeled soil-carbon gains were 0.36 ± 0.09 and 0.48 ± 0.11 Pg C year^{−1}, respectively, annualized over the mean 11-year study duration.⁵⁰

The spread among these estimates arises partly from model structure and the assumed response of plant production to grazing. The Century model used by Henderson et al. represents texture-dependent decomposition and equilibrium among organic matter pools but does not impose an explicit capacity on mineral-associated carbon stabilization.^{54–57} Powell et al.'s larger estimate applies one grazing-production-response curve and one low-to-moderate target grazing intensity across the global model domain within each simulation,⁵⁰ using parameter ranges derived partly from Milchunas and Lauenroth.⁵⁸ Moving to that target from heavy grazing can represent recovery, whereas moving to it from lighter grazing requires plant production to increase with grazing. Local conditions affect initial productivity, biomass ceilings, and soil-carbon predictions but do not assign the production response or target intensity. The net total is then restricted to pixels where modeled ecosystem carbon increases. The model therefore does not determine from local conditions where compensatory growth occurs. Across experiments and global syntheses, plant-production and soil-carbon responses vary in direction and magnitude with grazing intensity, climate, soil texture, and vegetation composition.^{27,28,59,60} These controls correspond to large regional differences. Ren et al. estimated grazing-associated soil-carbon losses of 23.4% in tropical regions and 15.2% in temperate regions.²⁸ Across Australian rangelands, rainfall and soil properties dominated soil-carbon stock variation, leaving smaller management effects difficult to detect.⁶⁰

The studies behind the most striking field claims are themselves atypical. Some of the highest reported rates come from degraded, irrigated, and fertilized soils measured in brief post-establishment windows, and they decline as soils re-equilibrate.^{53,61} Ren et al. estimated spatially varying optimal grazing intensities but cautioned that these values depend on land-use history and biotic and abiotic conditions and that the underlying correlations do not establish causation.²⁸ Together, these limitations mean that global modeled gains do not by themselves establish reliable management targets.^{28,39,50}

Stanley et al. attribute decades of “confusion rather than consensus” to poorly defined grazing metrics, incomplete representation of plant and soil processes, sampling design, and limited producer inclusion.⁵¹ Their framework seeks to explain variation in soil-carbon response well enough to optimize grazing for sequestration and support scalable prediction. We treat spatial and temporal heterogeneity in disturbance, vegetation, and management as a functional property that must be sustained whether or not it maximizes soil carbon.

HETEROGENEITY MAY SUSTAIN SOIL-CARBON PERSISTENCE

If productivity gains are an unreliable foundation, grazing may still support soil carbon by contributing to heterogeneous disturbance patterns. Even where moderate grazing supports below-ground carbon by limiting root turnover induced by heavy defoliation,^{62,63} this benefit does not require uniform grazing pressure across a landscape. Localized, shifting episodes of intensive grazing can displace dominant plants while creating opportu-

nities for other species and functional groups, generating functional diversity.^{38,64}

We posit a cross-scale pathway (Figure 1) in which low-to-moderate grazing supports soil carbon by producing heterogeneous patterns of disturbance across space and time (Figure 1A). Selective foraging and uneven landscape use generate mosaics of vegetation structure, species composition, and disturbance history.^{38,64,65,66} In tallgrass prairie, for example, year-round continuous grazing by reintroduced bison increased native plant richness by roughly 100% at the plot scale relative to ungrazed rangeland, with cattle producing a smaller increase, and the bison-driven gains recovered to their pre-drought trajectory after an extreme drought⁶⁷ (Figure 1B). These mosaics create a patchwork of plant communities, each with different functional traits, including root depths, exudate compositions, litter chemistries, and phenologies, which may—where they raise the functional-trait diversity expressed across the landscape—diversify the type, timing, and location of organic inputs reaching the soil.^{68,69,70} Experimental grasslands show increasing net soil-carbon accumulation with plant species richness⁶⁸ (Figure 1C), while global analyses indicate that the strength of this relationship varies with climate.⁷¹

In this view, persistence is an emergent property of the soil system wherein organic matter endures through the diversity of compounds, organisms, and microsites that constrain decomposition.⁷⁵ At finer scales, plant functional diversity translates to variation in litter composition, root architectures, and exudates (chemical compounds released by roots into surrounding soil), all of which shape microbial communities and the processes through which soil organic matter forms^{76,77} (Figure 1D). Much soil organic matter is microbial in origin: microbial communities transform plant inputs into biomass and residues, and microbial necromass can constitute over half of soil organic carbon in grasslands.^{78–80} Microbial carbon-use efficiency and other microbial traits influence how much soil organic matter forms^{73,81} (Figure 1E). Association with minerals and physical inaccessibility within aggregates can slow decomposition.^{75,82,83}

Mineral properties constrain the formation of mineral-associated organic carbon, but observed upper boundaries also reflect carbon inputs, climate, and other site conditions.^{77,84} Globally, many soils remain below estimated mineralogical capacity, and soils farther below that estimate generally accrue carbon more rapidly following management changes.⁸⁴ Where mineral-associated storage responds weakly to additional inputs, plant-diversity effects are hypothesized to occur mainly through the particulate pool.⁷⁷ In one 35-year calcareous grassland experiment, seasonal sheep grazing produced no detectable difference in mineral-associated or total soil carbon relative to ungrazed plots; the authors inferred that near-saturation of mineral surfaces could explain the result.⁸⁵ The relevant question is therefore whether these forms of diversity sustain the processes that allow whatever carbon is present to persist under perturbation. Heavy grazing is associated with declines in soil carbon, although these studies do not identify the loss of heterogeneity as the cause.^{28,86–89} In one meadow-steppe experiment, grazing reduced the spatial heterogeneity of microbial community structure and enzyme activity,⁹⁰ suggesting one route by which

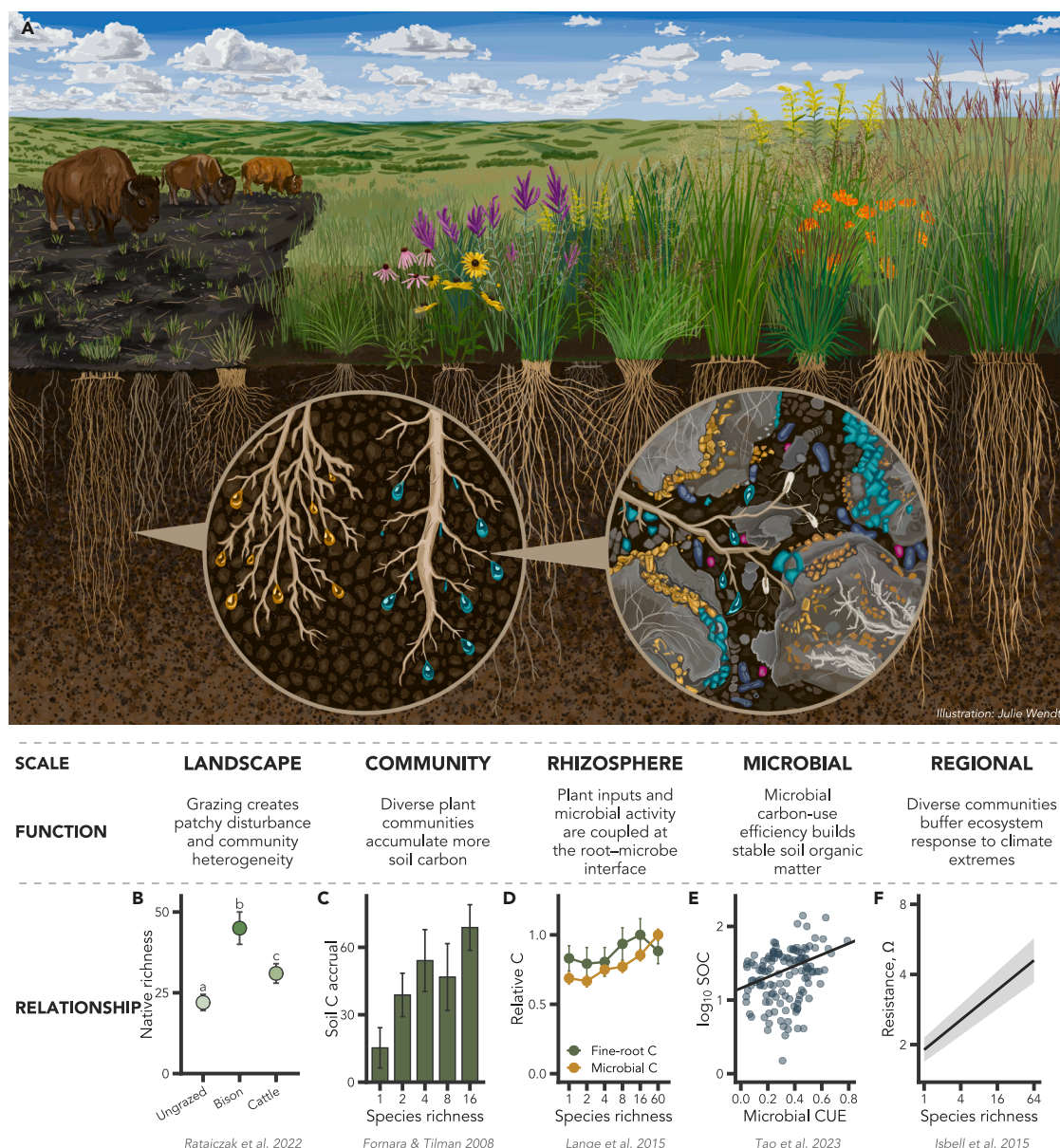


Figure 1. A hypothesized cross-scale pathway by which ecological heterogeneity may sustain soil-carbon persistence

The relationships in (B)–(F) are each individually documented, but they have not been assembled or tested as a single pathway in grazed rangelands, and they come from different systems.

(A) Conceptual schematic of a tallgrass prairie: a grazing-maintained landscape mosaic aboveground, and a soil cross-section below with magnified views of rhizosphere processing and mineral-associated stabilization of microbial residues (left and right insets, corresponding to the rhizosphere and microbial scales in D and E).

(B–F) Independent lines of evidence for individual links, drawn from different studies and systems and arranged to follow the proposed pathway: from the landscape mosaic (B) through community (C), rhizosphere (D), and microbial (E) processes to the regional-scale climate buffering it is proposed to support (F). Symbols are means; error bars are 95% confidence intervals in (B) and ± 1 SEM in (C) and (D). (E) shows individual observations with the regression reported by the source; (F) shows the synthesized mixed-effects trend and its 95% confidence band on log-log axes. (B) In tallgrass prairie, reintroducing bison increased native plant species richness (spp. 10 m^{-2}) relative to ungrazed plots ($\approx 103\%$ higher at the plot scale, $\approx 86\%$ at the catchment scale), with cattle producing a smaller increase ($\approx 41\%$); treatments sharing a letter do not differ significantly (Tukey's HSD, $\alpha = 0.05$).⁵⁷ (C) In a sown experimental grassland, net soil-carbon accumulation ($\text{g m}^{-2}\text{ year}^{-1}$) increases with plant species richness.⁶⁸ (D) In a sown experimental grassland, fine-root carbon and microbial biomass carbon (each scaled to maximum) are both elevated at higher plant species richness.⁷² (E) In a global model-data analysis, soil organic carbon increases with microbial carbon-use efficiency.⁷³ (F) In grassland biodiversity experiments, plant species richness increases the resistance (Ω , the ratio of normal productivity to its deviation during a climate event) of productivity to climate extremes,⁷⁴ a determinant of soil organic carbon formation. Illustration in (A) by Julie Wendt.

spatially uniform grazing could narrow soil-carbon formation pathways.

This relationship parallels mechanisms identified in research on biodiversity and ecosystem function. Different species contribute distinct organic compounds that are stabilized by different mechanisms.^{72,73,75} Community manipulations show that microbial communities of differing composition produce organic matter of differing chemical character and thermal stability,⁹¹ and loss of microbial diversity destabilizes the biogeochemical functions, including carbon assimilation, that these communities sustain over time.⁹² Diverse inputs also provide an insurance effect, sometimes termed response diversity.³¹ The strongest evidence for this insurance effect comes from plant productivity^{74,93,94} (Figure 1F), but the same logic is beginning to be documented belowground. In a comparison of extensively and intensively managed soils, more fungal-dominated and more even microbial communities lost less carbon and nitrogen under drought.⁹⁵ In a long-term Trans-Himalayan exclusion experiment, removing large herbivores raised the interannual variability of soil carbon and nitrogen by 30%–40%, which suggests that grazing can buffer soil carbon against year-to-year fluctuations in at least some systems.⁹⁶

Through this functional redundancy, heterogeneous systems may buffer carbon against disruptions that could not be absorbed by a narrow set of pathways. Grazing exclusion, which may increase plant cover or productivity, does not necessarily restore the structural complexity generated by patchy disturbance patterns.^{97–99} Selective grazing can amplify existing spatial variation in vegetation by concentrating use in some patches while leaving others lightly grazed.^{38,100} Heavy grazing can override that selectivity by removing most available biomass.³⁸ Some carbon-centric grazing systems deliberately reduce selectivity to promote more uniform forage utilization.¹⁰¹ Both heavy grazing and management for reduced selectivity may therefore narrow the disturbance variation relevant to soil-carbon persistence as climate conditions shift.

The component relationships are documented separately across scales. It remains untested whether landscape-scale heterogeneity propagates to the within-soil diversity that supports persistence and whether that connection holds as climate forcing pushes systems toward thresholds. We therefore advance the heterogeneity-persistence link as a hypothesis and research priority.

CLIMATE DYNAMICS OVERWHELM MANAGEMENT EFFECTS

The case for carbon-centric grazing rests on the assumption that soil-carbon stocks can be stabilized and incrementally increased through management, even as climate shifts. But this assumption underestimates how large and how fast climate-driven changes to soil carbon can be. Even if implemented globally, the effects of carbon-centric grazing on soil carbon would be overwhelmed by climate forcing across four interacting dimensions (Figure 2).

First, projected climate-driven soil-carbon losses exceed modeled grazing benefits except when compensatory plant growth is imposed across a global rangeland model domain (Figure 2A). Ren et al. project net losses of 0.22–0.53 Pg C year^{−1} across all soils, equivalent to 0.81–1.94 Gt CO₂equiv year^{−1}.¹⁰²

Henderson et al.'s modeled soil-carbon gain under perfect targeting of forage-maximizing grazing changes is 0.15 Gt CO₂equiv year^{−1}, but the intervention becomes a net source of 0.57 Gt CO₂equiv year^{−1} when additional forage is assumed to increase animal numbers and emissions proportionally.³⁹ The simulation assumes that climate-driven changes in greenhouse-gas fluxes over its 20-year horizon are modest relative to management effects.³⁹ Powell et al. estimate 0.37 ± 0.22 Gt CO₂equiv year^{−1} under constant plant production with local feed replacement and 1.83 ± 0.45 Gt CO₂equiv year^{−1} when the same compensatory plant-production response function is applied across the global rangeland model domain and livestock production is balanced within countries.⁵⁰ Because the response curve and target intensity are not assigned from local conditions and pixels with modeled ecosystem-carbon declines are excluded, the estimate does not establish where compensatory growth would occur under field conditions or whether the modeled net gains are locally realizable.

Second, higher temperatures act directly on decomposition of existing soil carbon, whereas grazing changes stocks through plant inputs, removal, redistribution, and soil disturbance (Figure 2B). Temperature-sensitive decomposition is one of several pathways through which soil-carbon losses can occur rapidly. Decomposition rates double to triple with each 10°C increase,¹⁰³ though apparent field sensitivities are often lower because substrate availability and physical and chemical protection can constrain the response. Where altered grazing may increase soil carbon through greater plant inputs, those inputs must be processed and stabilized before they add to persistent stocks.^{75,76,80} Global syntheses show a nonlinear, mostly negative mean stock response to grazing intensity whose direction and magnitude vary with climate and ecological context.^{28,58}

Third, the timescales of carbon accumulation and loss are deeply asymmetric (Figure 2C). Soil organic matter builds slowly through gradual processes^{75,80,83,104} but can be lost rapidly once thresholds are crossed.^{105–107} Even soil carbon that has persisted for millennia remains vulnerable to climate perturbations that exceed critical thresholds (Figure 2D).^{106–108,122–124} Shifts toward warmer and wetter conditions after the last glacial period destabilized soil carbon across the Ganges-Brahmaputra basin,¹²³ and climate transitions during the late Quaternary triggered persistent carbon losses in many regions.¹²⁵ Recent evidence suggests that today's apparent carbon deficits reflect these legacy losses, challenging the idea that current soils are underperforming merely due to mismanagement.¹²⁵

Fourth, climate variability undermines the mechanisms carbon-centric grazing depends on, and management lag compounds the risk. Drought suppresses growth needed for recovery after grazing, especially under recurrent extremes.^{109,110} Intense precipitation and wind accelerate erosion of carbon-rich surface layers, particularly under intensive grazing.^{111–114} Heat stress disrupts microbial communities,^{115,116} and shifts in precipitation seasonality and phenology decouple grazing from peak productivity.^{117–119} These disruptions are nonlinear and can cross ecological thresholds beyond which recovery is unlikely, regardless of grazing management (Figure 2E). Grazing decisions, meanwhile, are triggered by short-term surface signals (forage availability and livestock performance) that lag deeper processes governing carbon stability and are further constrained by seasonal rhythms, markets, and

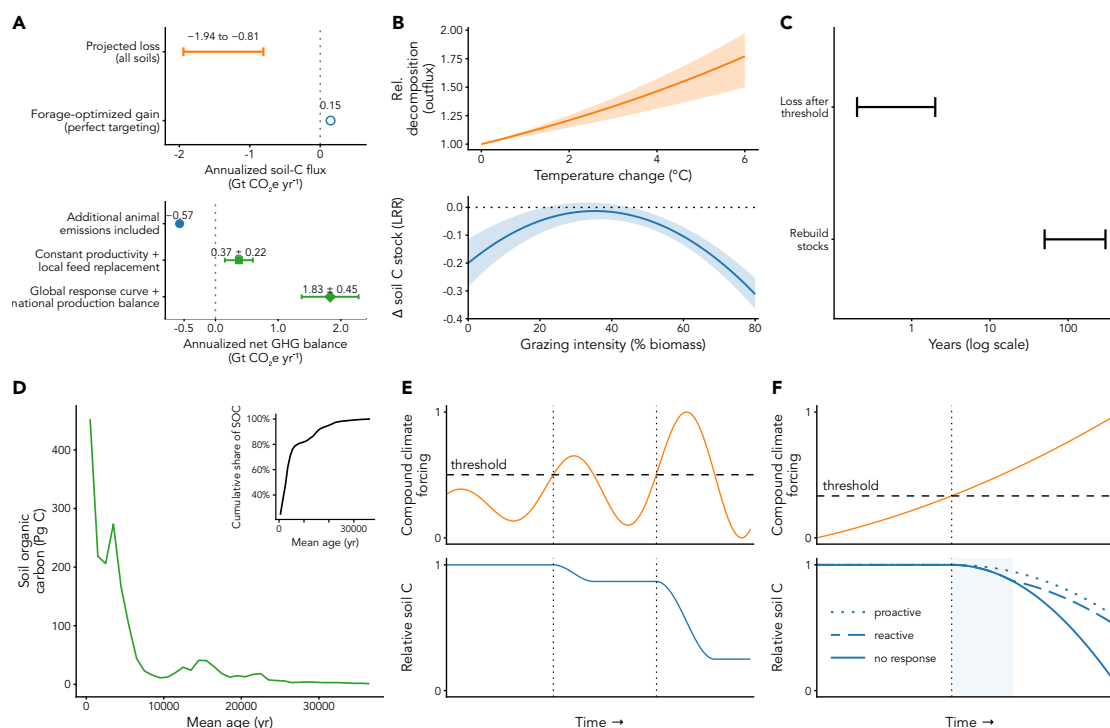


Figure 2. Climate forcing relative to grazing-mediated soil-carbon control

(A) Annualized projected soil-carbon loss and modeled grazing outcomes. Top: mean annualized projected loss across all soils (orange)¹⁰² and Henderson et al.'s maximum modeled gain under perfect targeting (blue).³⁹ Bottom: Henderson et al.'s net result after added animal emissions, and Powell et al.'s net estimates under constant productivity, with local feed replacement or a globally applied production-response curve with national production balancing (green).⁵⁰ Estimates cover different areas and system boundaries and are not an offset calculation. Orange shows the range across emissions scenarios; green points and bars show mean $\pm$ SD. (B) Temperature sensitivity of decomposition (top)¹⁰³ and the nonlinear, mostly negative global mean stock response to grazing intensity (bottom).²⁸ The orange band spans Q10 values of 2–3; the blue band is a cubic fit to the digitized 95% confidence interval reported by Ren et al.²⁸ (C) Timescales of soil-carbon loss and recovery. Bars span the approximate range of reported timescales (log scale): losses occur within months to years once thresholds are crossed, whereas rebuilding spans decades to centuries.^{75,80,104–108} (D) Estimated global 0–1 m soil organic carbon stock across bulk radiocarbon mean-age classes; the inset gives the cumulative share of the stock.¹⁰⁸ (E) Threshold-driven loss (schematic): climate variability produces compound forcings that intermittently exceed thresholds (top), driving stepwise declines in soil carbon following each threshold crossing (bottom).^{109–119} (F) Reactive lags (schematic): a threshold crossing in the forcing (top), and divergent trajectories of soil-carbon under proactive, reactive, and no response (bottom).^{120,121}

permitting (Figure 2F). Even well-intentioned responses arrive after the fact and at smaller magnitude than the driver.^{120,121} The result is late action against a moving target, with cumulative losses that management cannot offset.

If management cannot control the largest drivers of soil-carbon change, the goal of maximizing carbon inputs is misplaced. However, management can influence the capacity of rangeland social-ecological systems to absorb disturbance, reorganize, and retain function as the climate shifts. Such capacity depends on the diversity of stabilization pathways, not their optimization. Yet the same policy frameworks that promote carbon-centric grazing work against this capacity by suppressing the heterogeneity that sustains it.

STANDARDIZATION MAY ERODE ADAPTIVE HETEROGENEITY

How rangeland systems maintain function as climate changes depends on whether management preserves or erodes the flex-

ibility adaptation requires. When grazing management is organized around credited or policy-rewarded soil-carbon gains, attribution and verification requirements make carbon outcomes increasingly central to what practices are recognized and sustained. This reorientation risks reducing the strategies available to land stewards to respond to environmental variability.

The history of natural resource management offers ample warnings. From forests to fisheries, well-intentioned efforts to dampen variability and eliminate inefficiencies often produce what Holling and Meffe³² described as a pathology of natural resource management: regimes that suppress natural variation lose resilience and become vulnerable to the crises they were designed to prevent.^{126–129} In wetland mitigation banking, verification relies on rapid assessments of selected, readily measured site characteristics to produce comparable credits for ecological functions that remain difficult to compare across sites.¹³⁰ Carbon-centric grazing risks reproducing this narrowing of ecological and management vision. Although carbon crediting is nominally a market-based, decentralized instrument, its reliance on

Table 1. Three strategies for managing rangelands as heterogeneous adaptation reserves

Strategy: retain and regenerate heterogeneity through interacting disturbances Function and scale: sustains spatial and temporal variability in vegetation and soils at the landscape scale, maintaining multiple ecological functions and a diversity of carbon-stabilization pathways Representative example: patch-burn grazing and Indigenous burning that produce shifting vegetation mosaics (Box 3) Failure mode it guards against: homogenized disturbance that narrows ecological function and erodes the heterogeneity that underpins adaptive capacity and possibly carbon persistence
Strategy: enable responsiveness through flexible technologies Function and scale: extends what managers can observe and how quickly they can act, expanding response variety to track environmental variety at operational scale Representative example: satellite-derived forage and water maps delivered to herders (e.g., AfriScout in northern Kenya); precision-ranching sensor networks Failure mode it guards against: management lag and standardized signals that leave managers unable to track climate variability or that narrow the available responses
Strategy: sustain capacity through collaborative networks Function and scale: maintains the social structures that sustain variation, transmit knowledge, and coordinate without enforcing uniformity at institutional scale Representative example: transhumant grazing networks in the Sudano-Sahel; community-based pasture user groups in Mongolia Failure mode it guards against: institutional standardization and single-commodity policy that centralize decisions and erode the diversity of practice adaptation requires

standardized metrics, models, and practice prescriptions can narrow management and ecological variation as much as command-and-control regimes do, even as climate forcing pushes rangelands harder toward thresholds and self-reinforcing losses. Since the establishment of modern scientific management of rangelands in the early 20th century, attempts to apply simplistic models of vegetation and disturbance dynamics to complex, variable rangelands have repeatedly failed.^{120,131–135}

Carbon accounting can penalize disturbances that sustain heterogeneity. Many rangelands depend on recurrent fire to maintain herbaceous dominance, prevent woody encroachment,^{136–138} and produce pyrogenic carbon, a chemically distinct soil-carbon fraction whose stable component persists on centennial to millennial timescales.^{139,140} Without fire, woody plants expand and shift carbon from durable belowground pools to aboveground biomass vulnerable to catastrophic loss.²⁹ Carbon-accounting frameworks that measure only bulk carbon can mistake this redistribution for sequestration, penalizing disturbance regimes that sustain more persistent forms of soil carbon.¹⁴¹

Adaptive multi-paddock (AMP) grazing and related short-duration, high-stock-density systems are among the grazing strategies promoted for soil-carbon sequestration.^{51,142} AMP management can create differences in grazing timing and recovery among paddocks as managers respond to observed conditions.^{101,142} In carbon-oriented formulations, those adjustments follow selected indicators of forage use and plant recovery, with

soil carbon treated as an intended outcome.^{51,142} More uniform forage utilization and reduced selection of preferred plants have been described as intended outcomes of high-stock-density rotational grazing, including AMP systems.^{51,101}

All grazed systems face a fundamental management dilemma in that they must balance the competing processes of plant production and forage utilization.³⁶ Adjustments to timing, frequency, and duration of grazing remain tactically important. But this balance remains constrained by livestock demand for forage and by forage production that fluctuates with climate. Beyond grazing prescriptions, carbon-oriented programs introduce additional risks through input-driven interventions and accounting schemes that can further constrain management flexibility (Box 2).

HETEROGENEITY AS A PATHWAY FOR FUTURE ADAPTATION

We propose orienting future rangeland management around adaptation at landscape and network scales, moving from efforts to maintain fixed states toward strategies that can accommodate change.¹¹ This reorientation will not be easy. Elements of rangeland science and management have long emphasized stability and control. Even as theory has evolved to recognize variability, non-equilibrium dynamics, and multiple states,^{38,132,133,149} many practices assume predictability and linear response.

We identify three strategies (Table 1): retaining and regenerating heterogeneity through interacting disturbances, enabling responsiveness through flexible technologies, and sustaining capacity through collaborative networks. Together, these inter-related strategies sustain variability, keep management responsive, and distribute knowledge. They do not guarantee stability, but they expand the range of possible futures that rangeland systems can endure and even shape.

These strategies describe capacities—they are not practices that should be standardized. Funding tied to prescribed actions or measured outcomes makes compliance an additional definition of success: managers are rewarded only for responses the program recognizes.^{25,130} Economic incentives can weaken or reinforce pre-existing conservation motivations. Reported effects vary with payment form and whether the payment preserves or reduces participants' autonomy.^{150,151} Funding arrangements compatible with heterogeneous adaptation reserves would leave managers able to revise actions as conditions change, allow outcomes to vary across places and years, and retain monitoring for learning as well as verification.³³

Retain and regenerate heterogeneity through interacting disturbances

Adaptation depends on the ability of systems to reorganize.^{5,7,33} Rangeland heterogeneity reflects variation in soils, topography, and biotic interactions, together with disturbances that differ in duration, extent, and interactions with one another.^{38,127,152,153} The resulting spatial and temporal variation buffers environmental shocks and maintains multiple ecological functions.^{31,38,154} Management should retain existing disturbance interactions and re-establish spatial and temporal variation where suppression or standardization has narrowed it. When

Box 2. Risks of carbon-oriented policy for rangeland management

Carbon-oriented programs often extend beyond grazing prescriptions to include nutrient amendments (e.g., compost or synthetic fertilizer) and seeding of productive grasses or legumes as means to increase carbon inputs to rangeland soils.^{39,60,143} These interventions can elevate soil carbon near the surface in some contexts, but evidence for soil-carbon persistence, greenhouse-gas trade-offs, and heterogeneity of plant communities remains limited.⁶⁰ Such interventions are more typical of intensively managed or seeded grasslands than of extensive rangelands, but they illustrate how the logic of input-driven optimization narrows adaptive options by substituting engineered productivity for variability mediated by local conditions.

Carbon-accounting schemes introduce additional risks by formalizing the mismatch in scale between global metrics and local management realities. They may reward what certain stakeholders consider good stewardship, but they also shift responsibility for carbon losses, often driven by climate variability rather than management decisions, onto individual managers. Tying incentives or penalties to soil-carbon levels can expose managers to financial risk. Buffer reserves—pooled credits that markets withhold against reversals—work by diversifying independent, localized losses. Climate-driven soil-carbon losses are instead correlated across regions, so a drought or heat wave can deplete many projects at once. This kind of systemic reversal is difficult for a buffer pool to absorb.¹⁴⁴ Crediting further assumes that gains are additional and durable,¹⁴⁵ yet a reversal under drought or warming can negate credited carbon after it has been paid for.

In extensive rangelands, where pastoralists move livestock across landscapes, the link between stewards, their practices, and the ecosystem services for which they are paid becomes difficult to maintain, and movement between management areas is a measurement challenge.¹⁴⁶ The high spatial and temporal variability of rangeland soil carbon^{147,148} poses serious challenges for accurate, cost-effective measurement, potentially creating a system where managers are held accountable for changes they cannot reliably detect or control.

disturbance is suppressed or applied uniformly, adaptive capacity declines.^{32,129,132}

Interacting disturbances can regenerate heterogeneity at management-relevant scales.^{36,38,154} Patch-burn grazing and Indigenous burning practices illustrate this principle across diverse rangeland systems (Box 3). Disturbance applied in patchy, shifting patterns can produce vegetation mosaics that sustain ecological diversity and adaptive capacity. These regimes are not universally transferable. They must be historically informed, regionally adapted, and responsive to novel climate conditions that may render past disturbance patterns inapplicable.¹²

Landscape fragmentation further constrains where these regimes can operate. As fragmentation increases, sustaining heterogeneity becomes more costly. Where fire and herbivory remain coupled across larger areas, burned patches redirect herbivore use through changes in forage and fuel.¹⁵⁴ Roads, fences, conversion, and settlement constrain these dynamics, leaving spatial variation dependent on more deliberate coordination across smaller management units.^{37,137} Fixed physical fences require construction and maintenance, and reconfiguring them requires additional labor and materials.^{174,175} Virtual fences make boundaries movable but require collars, communication

infrastructure, and monitoring.^{174,175} Prescribed fire also requires labor, equipment, and coordination, which prescribed burn associations distribute across landowners.^{138,176} Once a patch is burned, changes in forage and fuel can redirect grazing without fixing subsequent disturbances to the same internal boundaries.¹⁵⁴

Trade-offs are inevitable in rangeland management because no single condition or disturbance regime can optimize all desired outcomes.³⁷ When disturbance is distributed across space and time, however, different landscape positions can serve different functions simultaneously.¹⁷⁷ In tallgrass prairie patch-burn systems, for example, recently burned patches provide high-quality forage for livestock while older patches retain residual structure and cover that supports some grassland birds and small mammals. These outcomes conflict under uniform management but coexist across a fire-grazing mosaic.^{154,178}

Enable responsiveness through flexible technologies

Climate variability can outpace management, so managers need to shorten the lag between a change in conditions and their response. Historically, pastoralists and ranchers have adapted to the inherent variability and unpredictability of rangelands through a blend of mobility (e.g., transhumance), buffering strategies (e.g., haying), and place-based knowledge. Digitally enabled tools now extend these approaches, providing multi-scale environmental data and enabling rapid responses to changing conditions.

Several technology classes are reshaping what managers can know and how quickly they can respond. Remote-sensing platforms provide continuous estimates of vegetation cover and production at resolutions of tens of meters.¹⁷⁹ Precision-ranching sensor networks integrate livestock tracking collars, water-level sensors, and weather-station data through wireless networks.¹⁸⁰ Climate-risk maps and forage forecasts are available at regional scales through tools such as Climate Engine and AussieGRASS.^{181,182} Together these tools shorten the lag between observation and action across landscapes too extensive and dynamic to monitor comprehensively with traditional methods.¹⁸³

Technologies should be evaluated by how they distribute or concentrate decision-making authority, not just by how much information they add. A system can regulate only as much variation as its own responses can match, a principle known as requisite variety.¹⁸⁴ Adaptive capacity therefore depends on whether the management system, from managers and animals to institutions and landscapes, generates enough response variety to track the conditions it faces. Where it cannot, intended outcomes become unreachable, and more information does not compensate. Remote sensing, mobile communication, virtual fencing, and AI-based decision support can expand response variety by extending observation, reducing decision lag, and enabling spatially precise action. But the same tools can also narrow it when they compress complex landscapes into a small number of standardized signals, shift authority away from local actors, or optimize management toward externally legible outcomes (e.g., aboveground carbon sequestration via tree plantings²⁹). Their value therefore depends less on technical sophistication than on whether they sustain response variety matched to the variety of conditions managers face.

Box 3. Disturbance-based adaptation across global rangelands

Patchy, shifting disturbance maintains vegetation mosaics across rangeland systems worldwide, a principle captured in the pyrodiversity-biodiversity hypothesis^{155,156} and extended to systems where fire and herbivory interact. In North American grasslands, patch-burn grazing concentrates livestock in recently burned areas, creating variation in vegetation structure and resource availability^{100,157} that supports biodiversity, forage quality, livestock performance, and wildfire controllability.^{158–164} Where burn locations shift among years, differences in time since fire and subsequent grazing accumulate within a management unit.^{100,154} In Great Plains systems, prairie dogs add longer-duration disturbance histories by altering vegetation and grazer distribution.¹⁵² In southern African savannas, fire and large herbivore grazing have long maintained vegetation heterogeneity across rainfall gradients, with fire dominating biomass turnover in mesic systems and herbivory in arid ones.¹⁶⁵ In northern Australian savannas, Aboriginal burning generates fine-grained mosaics that sustain biodiversity and reduce wildfire risk.^{166,167}

Fire and grazing compete for aboveground biomass; what is grazed cannot be burned. Lower forage utilization leaves more biomass available as a drought reserve¹⁶¹ or as fine fuel for prescribed fire where woody plant cover may be reduced.¹³⁸ Climate change is narrowing prescribed fire windows in some regions,^{168,169} while woody encroachment can reduce herbaceous fuel continuity.¹³⁶ Historical and paleo records underscore both the importance and limits of disturbance-based management. In Holocene Africa and North America, fire dominated biomass turnover in wetter, fuel-rich systems, and herbivores were the primary disturbance agents in drier, open regions.^{165,170} Consequently, each management approach is effective where the disturbance regime it recreates historically operated but may be less suited to systems shaped by other legacies. With atmospheric CO₂ concentrations now exceeding Holocene levels and approaching those of the Early Miocene, when North American grasslands first expanded,^{171,172} restoring past systems will in many cases be neither realistic nor necessarily desirable.¹⁷³

Whether a given tool expands or narrows response variety depends on how it is deployed. In northern Kenya, the AfriScout mobile app delivers satellite-derived forage and water-condition maps directly to herders' phones, informing migration decisions in response to seasonal and drought conditions across landscapes.¹⁸⁵ Ethnographic work from the early 2010s documented how mobile-phone networks restructured herding decisions in East African pastoral systems, allowing distributed coordination among households.¹⁸⁶ These applications inform herder decision-making, extending what managers can perceive while keeping authority over movement decisions with herders themselves. The same products, deployed within standardized verification regimes, translate observation into uniform prescriptions and shift authority from herders to compliance auditors.

Digital tools introduce vulnerabilities of their own, and their long-term value for adaptive capacity remains largely untested. Algorithms trained on past conditions may misfire under unprecedented climates. Subtler failures arise when products are used to answer questions they were not designed to address. Remotely sensed estimates of aboveground net primary production (ANPP) and standing biomass, for example, are easily conflated despite measuring fundamentally different quantities; the difference especially matters where vegetation cover is dy-

namic, as in most rangeland systems.¹⁸⁷ When failure occurs (through connectivity loss, hardware malfunction, or financial withdrawal), managers can be left without systems they have come to rely on. Rebuilding that capacity can be slow and uncertain if a tool has displaced local decision-making.^{32,126}

Bestelmeyer et al.¹⁸⁸ identify three persistent barriers to effective use: limited accessibility (awareness, cost, broadband and cellular coverage, and complexity); lack of trust in tools developed without stakeholder engagement; and a mismatch between the management problems users face and the technological support actually available. Addressing these barriers requires more than the tools themselves. Cooperative ownership models, public technical assistance, and low-cost platforms suggest pathways to broader access without concentrating control. Technology can expand the range of what managers can perceive, but networks determine whether that perception becomes adaptive action or standardized compliance.

Sustain capacity through collaborative networks

Because the pressures toward uniform management are ultimately institutional, the third task is to sustain the social structures that keep multiple management responses available, transmit memory, and coordinate without enforcing uniformity. Networks that reward variation can support adaptation by maintaining the conditions in which divergent practices can persist.^{33,189–193} In many rangeland regions, however, the social systems that once supported adaptive divergence have weakened. Rural depopulation, succession without apprenticeship, and the erosion of locally accountable channels for knowledge exchange reduce the density of feedback between working landscapes and the local knowledge needed to manage them, narrowing the range within which meaningful variation can be expressed.^{146,194}

Despite this erosion, collaborative arrangements endure in many pastoral systems globally. In the Sudano-Sahelian region of West Africa, transhumant pastoralists move livestock hundreds of kilometers between northern wet-season pastures and southern dry-season pastures, with routes responding flexibly to spatially variable rainfall.¹⁹⁵ Grazing rights are organized around water points and access is governed by reciprocity, with outsiders granted use under the obligation to extend the same access when circumstances are reversed.^{195,196} The aggregate effect of these decentralized decisions is a spatiotemporal distribution of livestock that responds to year-to-year variability and that no centralized regime could specify in advance.¹⁹⁵

Similar logic appears in Mongolia, where pastoralists move seasonally among winter, spring, summer, and autumn pastures and extend reciprocal access during severe drought or winter storms.¹⁹⁷ After post-socialist institutional decline, community-based rangeland management has been rebuilt across some districts. Where they have been established, pasture user groups organize grazing among member households, supported by a state-adopted monitoring system.¹⁹⁸ Comparative studies across hundreds of groups document that members access more diverse information, set local rules, and show measurably greater adaptive capacity during winter disasters.^{199–201} Direct vegetation and soil signals from these management changes

are weaker and harder to attribute,²⁰² consistent with evidence that decadal-scale climate variability is a stronger driver of rangeland conditions than grazing management.²⁰³ In these districts, community-based management has rebuilt social infrastructure that sustains heterogeneity of practice and the adaptive capacity that depends on it.

These arrangements share a pattern of decision-making across many actors at different scales that allows the pastoral system to track environmental variability without centralized prescription.^{146,196,204} Reid et al.¹⁴⁶ reframe the canonical tragedy-of-the-commons debate accordingly, arguing that the genuine failure modes in pastoral systems are a tragedy of open access, when rules of use are absent, and a tragedy of enclosure, when commons are privatized and fragmented into boundaries that block mobility and homogenize use. Both erode variation that is mutually sustained by distributed governance and heterogeneous landscapes.

Distributed governance is not necessarily self-protecting. Ideas that spread quickly can displace alternatives before they are tested, and tight feedbacks between performance metrics and decision-making accelerate learning when variation is preserved but amplify error when it has been suppressed.^{205–207} These dynamics intensify when standardized metrics become the primary signal coordinating across actors.

State and market pressures push pastoralists toward fixed settlements, private holdings, and formal rules. This fragmentation echoes historical enclosure but operates across much larger areas. In the Sudano-Sahelian region, successive land-tenure reforms have transferred management nominally to local communities while enabling land sales to agribusiness and shrinking pastoral access to seasonal reserves, with widespread reports of farmer-herder conflict over remaining corridors.²⁰⁸ Carbon-centric natural climate solutions are an emerging variant of the same pattern. In the Sahel, afforestation programs promoted as climate mitigation have blocked customary livestock migration routes and obstructed pastoral access to water.²⁹

Adaptation requires social structures that support locally situated knowledge and protect heterogeneity of practice, outcome, and interpretation across scales. Such structures cannot be optimized into existence by external policy. Where they have weakened, they must be sustained or rebuilt by strengthening local leadership, rules, and channels for knowledge exchange in ways that keep authority with the actors who make and adjust management decisions in concert.

OUTLOOK

Climate variability in the coming decades is unavoidable and likely to intensify. Soil-carbon gains are finite and vulnerable to reversal under continued climate forcing. Their limited and uncertain mitigation potential does not justify the risks of standardizing rangeland social-ecological systems to credit them. The largest carbon benefit these systems offer is already secured by keeping them intact, since converting pasture or native vegetation to cropland can release on the order of 40%–60% of soil-carbon stocks.¹⁵ Grazing's further influence on soil carbon is small and, under continued climate forcing, cannot be assumed to be durable. Managed for heterogeneity rather than optimized

for carbon, rangelands sustain biodiversity, food production, and rural livelihoods, along with whatever long-term carbon persistence is achievable. Carbon and adaptation are then largely compatible at the level of management.

Three lines of work emerge from this analysis. First, the heterogeneity-persistence linkage needs direct empirical test. Biogeochemical analyses of organic matter fractions, molecular markers, and compound-specific isotopes across rangeland conditions can show whether more heterogeneous, disturbance-maintained landscapes form more chemically diverse organic matter than uniform ones. Whether such diversity also sustains persistence under continued change is a harder question, requiring observations that follow the same system over time. Second, carbon markets and conservation programs rely on verification protocols that operate at parcel scales and on fixed-target metrics that constrain heterogeneity-based management. Developing alternatives appropriate to the spatial and temporal scales at which adaptive capacity operates remains an open research and policy challenge. Third, sustaining institutional infrastructure that supports divergent practice would strengthen the social foundations of heterogeneity-based management.

Global rangeland management cannot by itself alter the trajectory of climate forcing, but it can sustain the conditions under which ecosystems absorb disturbance and reorganize. Those conditions depend on variability in disturbance regimes, in management responsiveness, and in the networks that sustain divergent practices. Rangelands managed as heterogeneous adaptation reserves provide this capacity through the deliberate preservation of variability across scales.

Data and code availability

This study did not generate new data. The values plotted in Figures 1 and 2 were digitized or computed from the publicly available sources cited in the figure legends; code used to render the figures is available from the lead contact on request.

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AUTHOR CONTRIBUTIONS

J.A.F.W., S.D.F., and A.F.C. conceived the perspective; all authors contributed to the literature synthesis; J.A.F.W. drafted the original manuscript; and all authors contributed to review and editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION PROCESS

During the preparation of this work, the authors used Claude (Anthropic) and Codex (OpenAI) to assist with editing and reorganization of the text. The authors take full responsibility for the content of the publication.

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